

Advances in Photonic Crystals and Devices

Edited by
Narendra Kumar
Bhuvneshwer Suthar

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Foreword



電子及計算機工程學系
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The present book *Advances in Photonic Crystals and Devices*, edited by Dr. Kumar and Dr. Suthar is a collection of different chapters from different experts working in the field of photonic crystals, which, with precise editing, can be a substantial volume of good standard in the field. In recent years, the study of the physical and optical properties of photonic crystals has generated a burst of new ideas in designing new optical devices. This book is a collection of 15 chapters with introduction as well as research and device application-based contents that have received a considerable attention during the last years regarding the basic understanding, fabrication, and characterization of photonic crystals.

First, [Chapters 1](#) through [9](#) included in the book deal with the study of the fundamental properties of photonic crystal and photonic crystal fiber based on the various parameters. In brief, the book begins with basics of photonic crystal fiber and its modal and structural parameters for two different materials. It further includes the transmission and filtering properties of one-dimensional photonic crystal containing positive and negative index materials. A nonlinear optics and supercontinuum generation in photonic crystal fibers is also described. New materials such as magnetized cold plasma in bulk and metamaterials are considered to determine the features of photonic crystals. One-dimensional photonic crystal with liquid crystal defect embedded with grapheme layers is also discussed. Second, this book covers introduction to the device-based applications of photonic crystals. [Chapters 10](#) through [15](#) are focused on the device-based applications of photonic crystals, such as sensor, demultiplexer, logic gate, and biomedical sensing applications. Throughout the book, the authors have used various approaches to discuss different types of photonic crystals and their applications, for example, plane wave expansion method (PWEM), transfer matrix method (TMM), finite difference time domain (FDTD), effective index method (EIM), and some others. A number of references have been cited to see more about the topic and language used throughout the book are standard while it is easy to understand.

This book will be highly beneficial for beginners in the field like students pursuing masters in photonics and is especially designed for the researchers working in the area of theoretical modeling of photonic crystals and fabricating nanophotonic devices. This book will prove as the benchmark and updated text in the field for years to come.

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Preface

The pioneering works of Yablonovitch and John in 1987 have initiated an extended and phenomenal development in the field of photonic crystals (PCs) over the last two decades, and there have been a number of recent advances in PCs, which plays a main role in designing optical devices. They are periodically structured electromagnetic media consisting of periodic variation of dielectric constant, which prevent certain electromagnetic wave frequency ranges, due to the scattering of propagating wave, called photonic band-gaps (PBGs), to propagate through them. PCs elicited numerous interesting features for modeling the flow of light, and their exploitation is a promising tool in nanophotonics, optical computing, and sensors despite their many applications such as optical engineering, omnidirectional reflectors, optical switches, narrow-band filters, waveguide splitters, resonance cavity, lasers, optoelectronic circuits, and nonlinear filters.

The book is composed of 15 chapters, which shows an in-depth knowledge of the basic concepts necessary to understand the features of different types of photonic crystals arising from the periodic PC structures with different kinds of materials, including magnetized cold plasma. It reviews the selective topics based on one-, two-, and three-dimensional PCs and also introduces their prospective scopes in designing optical devices. A large number of references are provided for students and researchers at the end of each chapter to get additional information regarding a particular topic.

This book deals with two different aspects of PCs, where [Chapters 1](#) through [9](#) are based on the basics of different types of photonic crystals, photonic crystal fibers, and their fundamental features, which are kept first, and further [Chapters 10](#) through [15](#) cover their applications in designing photonic devices. The book is organized in a following manner: [Chapter 1](#) begins with an introduction to photonic crystal fiber with its modal and structural parameters using an effective index method (EIM) for two different materials. [Chapter 2](#) provides a detailed account of the transmission properties of one-dimensional photonic crystal (1D PC) and discusses filtering capacity and band structure characteristics for 1D PC containing positive and negative index materials, where the number of transmission channels and their frequencies is modulated by controlling the structural parameters and incident angle. [Chapter 3](#) introduces optical properties of photonic crystal fibers using a mathematical model. [Chapter 4](#) is devoted to an analysis based on the nonlinear optics and supercontinuum generation in photonic crystal fibers. [Chapter 5](#) focuses on the tuning of photonic bands exhibited by magnetized cold plasma by changing various parameters. [Chapter 6](#) provides information on designing a broadband fiber-optic parametric amplifier based on near-zero ultraflat dispersion profile with single zero-dispersion wavelength using a selective liquid infiltration technique. In [Chapter 7](#), the property of electromagnetic density of mode in acoustically perturbed photonic crystal is described. [Chapter 8](#) is devoted to the theoretical study of optical properties of asymmetric 1D PC taking liquid crystal defect embedded with graphene layers. [Chapter 9](#) is focused on the optical properties of 1D PC considering a periodic structure containing dielectric and metamaterial with symmetrically introduced magnetized cold plasma defect.

[Chapter 10](#) presents a detailed overview of photonic crystals and their biomedical applications as optical sensors. [Chapter 11](#) elaborately reviews the design and characteristics of two-dimensional photonic crystal (2D PC)-based wavelength division multiplexing

(WDM) as demultiplexer. [Chapter 12](#) deals with the interference-based optical logic gates using photonic crystals, which describes the design principles and conditions of OR, AND, XOR, and NOT gates, and the working simulations are based on the finite-difference time-domain (FDTD) method. [Chapter 13](#) focuses on design of devices with 1D ternary photonic bandgap structures. [Chapter 14](#) discusses a design of interference-based all-optical photonic crystal logic gates, in which the T-shaped waveguide-based logic gates are interconnected in single- and double-stage structures to observe the complex functionality. [Chapter 15](#) provides the optical sensing applications in biomedical engineering and biophysics, which includes a case study of hemoglobin in human blood and proteus simulation made with respect to some parameters to see the output potential.

This book describes the basic background and maps out the frontiers of photonic crystals using different theoretical and experimental approaches in understanding unprecedented control and manipulation of light by different types of photonic crystals using a variety of materials and their applications in designing several optical devices. Although the book is useful for the researchers working in the fields of photonics, optical computing, and fabrication of nanophotonic devices, it is also intended for the students pursuing their master's degree in photonics and modern optics.

The editors are grateful to all the authors for their important contributions in the form of chapters, where some of them are unpublished works, and also for their valuable discussions regarding corresponding chapters. The editors extend their thanks to Prof. Dr. Ali Rostami, University of Tabriz, Iran, for his suggestion and help in publishing this book. They also thank the authorities of the corresponding universities of the editors, namely Mody University of Science and Technology, and MLB Government College, MGS University for their enthusiastic and enduring support in the successful completion of this book editing project in a given time frame. One of the editors (NK) wishes to express his gratitude to his father Er. Bhola Singh for the inspiration in the pursuit of academic excellence that made possible to achieve the goal. Although a strenuous effort has been made to avoid errors, the editors will be highly grateful to receive marking of errors and suggestions for further improvement of the book.

Narendra Kumar

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Editors



Narendra Kumar was born in 1976 in Pitro, a village located in Bhojpur district of Bihar, India. He received B.Sc. (Hons.) and M.Sc. degrees in Physics from Banaras Hindu University in 1996 and 1998, respectively. Prior to graduation, he completed his schooling from PTPS (Patratu) High School and St. Columba's College, Hazaribag, Jharkhand. He obtained a doctorate in Applied Physics from IIT-BHU in 2002. During his doctoral research, he worked on the propagation characteristics of some optical waveguides with new smart structures as well as one-dimensional photonic crystals. Dr. Kumar is an Assistant Professor (in senior grade) in the Department of Physics, School of Sciences, Mody University of Science and Technology, Lakshmangarh, Sikar, Rajasthan,

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Bhuvneshwer Suthar was born in 1983 in Bikaner, India. He received a B.Sc. degree in 2002 from MDS University, Ajmer, India and an M.Sc. degree in Physics in 2004 from the University of Bikaner, and a PhD degree in Photonics in 2011 from MGS University, Bikaner (formerly the University of Bikaner). He received the Junior Research Fellowship of CSIR, New Delhi, India during 2006–2008 and the Senior Research Fellowship of CSIR, New Delhi, India during 2008–2011. He has worked as an Assistant Professor in the College of Engineering & Technology, Bikaner during 2011–2012 and then in Govt. Engineering College, Bikaner during 2012–2018. At present, he is working as an Assistant Professor in the Department of Physics, MLB Government

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List of Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
AO	acousto-optic
BG HBF	bandgap-guiding highly birefringence fibers
BPM	beam propagation method
BWA	biological ware agent
CM	coherence multiplexing
CR	contract ratio
CW	continuous wave
CWAs	chemical ware agents
DNG	double negative
DPS	double positive
DR	dynamic range
EIM	effective index method
EM	electromagnetic
EPCC	extrinsic plasma photonic crystal
ESRI	elliptical sphere of refractive index
FBG	fiber Bragg grating
FDTD	finite-difference time-domain method
FEM	finite element method
FFT	fast Fourier transform
FOM	figure of merit
FOPA	fiber-optic parametric amplifier
FORS	fiber optics reflectance spectroscopy
FV-FEM	full-vector finite element method
FW BEM	full-wave boundary element method
FWHM	full width half maximum
FWM	four wave mixing
GHz	gigahertz
GVD	group velocity dispersion
HCF	hollow-core fiber
HC-PCF	hollow-core photonic crystal fiber
HNA	high numerical aperture
HNLF	highly nonlinear fiber
HR	high reflectance
ICT	information and communication technology
IG HBF	index-guided highly birefringent fiber
LC	liquid crystal
LHP	left-hand polarization
LIDAR	light detection and ranging
LIF	low index fiber
LMA	large mode area
LOD	limit of detection

MCP	magnetized cold plasma
MFD	mode field diameter
MI	modulation instability
MOFs	microstructured optical fibers
MRE	magnetorheological elastomer
MZI	Mach–Zehnder interferometer
NIMs	negative index materials
NOEMS	nano-opto-electro-mechanical system
OBG	omnidirectional bandgap
O-E-O	optical-electrical-optical
O-PCF	octagonal photonic crystal fiber
OTDR	optical time domain reflectometry
PBG	photonic bandgap
PBS	photonic band structure
PC	photonic crystal
PCF	photonic crystal fiber
PCG	phonocardiogram
PCRR	photonic crystal ring resonator
PCS	photonic crystal structure
PCW	photonic crystal waveguide
PDM	polarization division multiplexing
PML	perfectly matched layer
PPC	plasma photonic crystal
PPLN	periodically poled lithium niobate
PWE	plane wave expansion
RAHF	random air-hole fiber
RC	reflection coefficient
RDTS	Raman-based distributed temperature sensor
RHP	right-hand polarization
SC	supercontinuum
SE	spontaneous emission
SIF	step index fiber
SNG	single negative
SOA	semiconductor optical amplifier
SOI	silicon on insulator
SPM	self-phase modulation
SRS	stimulated Raman scattering
SSFS	self-frequency shift
TC	transmission coefficient
TE	transverse electric
THz	terahertz
TM	transverse magnetic
WDM	wavelength division multiplexing
XPM	cross-phase modulation
ZDW	zero-dispersion wavelength

1

An Introduction to Photonic Crystal Fiber: Modal and Structural Parameters

Dimpi Paul and Rajib Biswas

CONTENTS

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1.1 Introduction

Study of photonic crystal fibers (PCFs) focusing on their modal parameters with modifications in structural parameters currently holds the interest of researchers in the field of optical communications and sensing applications; thanks to their well-controlled configurations. PCFs comprise a wave-guiding core and a cladding with periodic array of innumerable air holes. These air holes are generally characterized by special lattice structures with a diameter (d) and a specific air hole-to-air hole spacing (pitch: Λ). Extensive research on PCFs is carried out because of their flexible design, tunability in parameters, endless single-mode operation, and several other unique properties. Unlike conventional optical fibers, PCFs can guide light by two mechanisms: total internal reflection (index guiding) and photonic bandgap (PBG) effect. The former is similar to the traditional total internal reflection in which the central core is made of a solid, which is again surrounded by numerous air holes in a regular triangular lattice. As a result, light is confined into the central region. In the latter, guiding of light depends upon coherent backscattering of light into the core.

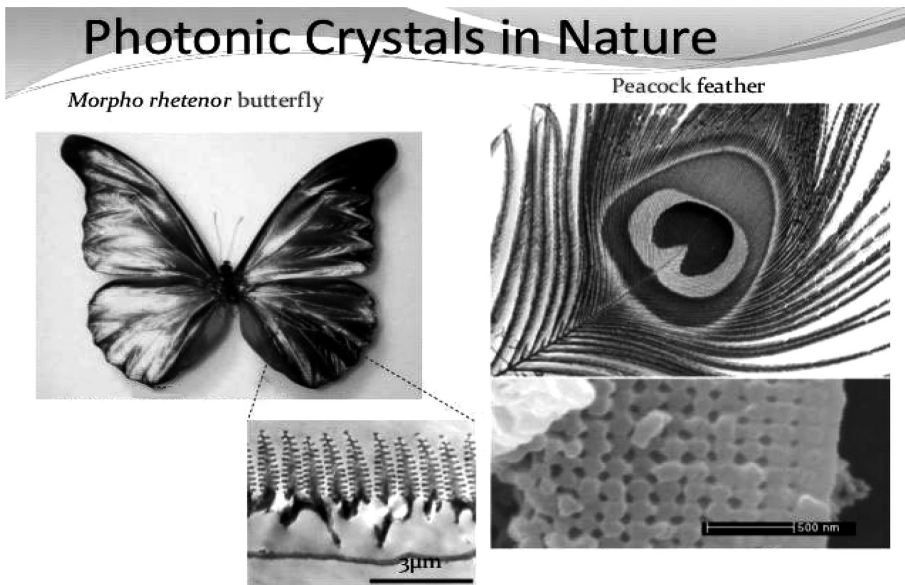
So far as study of wave dynamics in PCFs is concerned, there are several well-established methods mentioned in the literature. A few that give a fairly accurate study of PCFs are plane wave expansion (PWE) method, beam propagation method (BPM), finite difference time domain (FDTD) method, finite element method (FEM), and

effective index method (EIM). With regard to the guiding mechanisms mentioned earlier, appropriate selection of the wavelength window is very important because PCFs exhibit distinct characteristics under different window regimes. Besides the wavelength window, another parameter that affects propagation is the composition of the material. With variation in the compositional elements, the modal properties of PCFs are observed to be altered (Aristizabal et al. 2006; Broeng et al. 1999; Cregan et al. 1999; Dudley and Taylor 2009; Knight et al. 1996; Knight 2003; Poli et al. 2007; Russell and Roger 2001; Russell 2003; Saitoh and Koshiba 2005). Optimization of modal parameters is followed by designing and modeling of PCFs or microstructured fibers and has been an area of research interest from the past few years. Theoretical modeling of microstructured fibers helps the researcher to examine the modal properties entirely along with the sensing abilities before implementing an experiment. Prior to fabrication, the simulation of the microstructured fibers can help the researcher to choose specific geometrical parameters and operating wavelengths. Similarly, the selection of proper material compositions can be accomplished with theoretical study of microstructured fibers with an aim to control and improve the modal properties as well as minimize losses arising in different areas during experimental analysis. This chapter highlights designing of microstructured fibers with improved quality using two different material compositions, namely crown and phosphate. This improvement brings about changes in the sensing region of PCF-based sensors. The penetration depth can also be modified by altering the fiber geometry while building a sensing setup.

To observe the variation in sensing schemes, PCFs of dissimilar geometries have been incorporated in this analysis. The aim of this chapter is to study the performance of PCFs with respect to variable material composition, and its effect on the modal parameters with varying Λ and R_{eff} values, keeping structural parameters constant. The modal parameters under study are V parameter, spot size (w_{eff}), mode field diameter (MFD), effective mode area (A_{eff}), beam divergence (θ), and dispersion. Using a computationally efficient EIM technique, we outline the effect of modal parameters with certain dimensionless quantities such as d/Λ and λ/Λ in each material domain with respect to the geometrical parameters namely Λ and R_{eff} as constants, and in the variable domain as well. To estimate these parameters, we have adopted second and third telecom windows where, as dependent variables, we have chosen three different sets of pitches and diameters, which correspond to distinctive changes in the effective core radii in each material regime.

1.2 Origin of Microstructured Fiber and Guiding Mechanisms

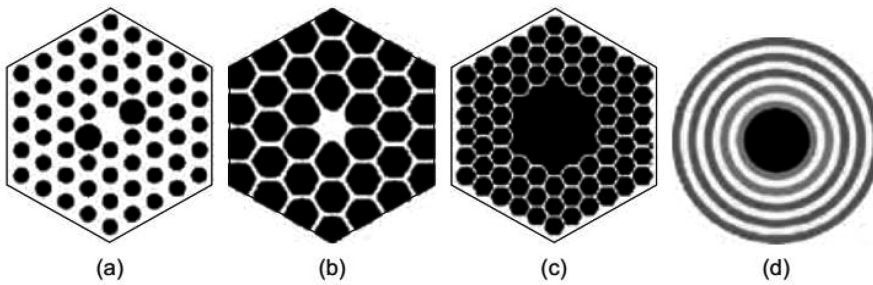
Since 1991, significant improvements in the performance of optical fibers have been observed, with the discovery of a new class of fibers called microstructured fibers (Cregan et al. 1999; Knight et al. 1996; Russell and Roger 2001). The concept of microstructured fiber was first established after the development of photonic crystals (Poli et al. 2007; Russell and Roger 2001). In the 1980s, the concept of photonic crystal (Figure 1.1) was of greater interest to researchers for developing a new and improved optical medium within the micrometer range (Poli et al. 2007; Russell and Roger 2001). Photonic crystals are composed of regular morphological microstructures that are periodically integrated, leading to

**FIGURE 1.1**

Naturally available photonic crystals. (Retrieved from Dudley, J.M. and Taylor, J.R., *Nat. Photonics*, 3, 85–90, 2009.)

special optical properties. [Figure 1.1](#) shows naturally available photonic crystals. Photonic crystals display PBG effect due to periodic variation in the refractive index of its material (Dudley and Taylor 2009; Poli et al. 2007; Russell and Roger 2001). In 1991, the concept of PCF was introduced by Phillip Russell (2003). The first working PCF was reported in 1996, and later, different types of PCFs were designed by several groups (Aristizabal et al. 2006; Russell 2003; Saitoh and Koshiba 2005). Unlike conventional optical fibers, the cladding of PCFs is made up of a number of air holes of a specific diameter, which occurs throughout the length of the fiber (Aristizabal et al. 2006; Broeng et al. 1999; Knight 2003; Saitoh and Koshiba 2005). There are certain parameters that characterize a PCF. For instance, we refer to the center-to-center spacing between the nearest air holes as the pitch Λ and the air-hole diameter as d .

The central defect is surrounded by several air holes in a triangular/hexagonal/circular lattice (Birks et al. 1997; Knight et al. 1998). The index guiding mechanism depends on the contrast in the refractive indices between the core and the cladding, similar to conventional fibers. Air-guiding PCFs possess a periodic structure of air holes with a hollow central defect. The PBG effect occurs only when there exists a huge contrast in refractive indices between the core and the cladding of a microstructured fiber (Russell 2007). With respect to the design flexibility, hollow-core PCF provides low-loss guidance by limiting the conventional propagation technique (i.e., total internal reflection [TIR]) in a single-mode regime (Russell 2007). Similarly, solid-core PCF provides a smaller mode volume, which allows for higher effective nonlinearities and higher birefringence (Russell 2007). Moreover, irrespective of solid and hollow cores, PCFs can perform single-mode operations over a wide range of wavelengths with considerable diminution in chromatic dispersion (Aristizabal et al. 2006; Saitoh and Koshiba 2005). Due to such tunable configurational properties of PCFs, they are now implemented in multitude of sensing schemes based on the surface plasmon resonance ([Figure 1.2](#)).

**FIGURE 1.2**

Types of available photonic crystal fiber drawings of various structures: (a) birefringent photonic crystal fiber (PCF), (b) ultrasmall core photonic crystal fiber (PCF), (c) hollow-core photonic crystal fiber (HC-PCF), and (d) hollow-core Bragg photonic crystal fiber (PCF). (Retrieved from Russell, P., *IEEE Leos Newsletter*, 21, 11–15, 2007.)

1.3 Literature Review on Modal Properties

In 2003, Hwang et al. reported modal characteristics of PCF using the PWE method (Shi et al. 2004). After a few years, Saitoh, K. and M. Koshiba in 2005, proposed a numerical approach to study PCFs and provided a brief overview on their progress, entailing numerical modeling techniques (Saitoh and Koshiba 2005). Three different approaches, such as effective index, basis-function expansion, and numerical approaches were utilized by this group to describe the fundamental properties of PCFs (Saitoh and Koshiba 2005). Simultaneously, Arriaga (2005) reported the guided modes of PCF using the effective index model. Similarly, he established a comparative study of V -parameter values using effective indices of the propagating modes and the space-filling mode (Arriaga 2005). Aristizabal et al. (2006) presented a numerical approach based on the scalar finite element technique for the solid-core PCF (Limpert et al. 2003; Uranus and Hoekstra 2004). They analyzed the modal properties of solid-core PCFs having refractive index discontinuity between the core and air holes using scalar solution and polarization correction (Ortigosa-Blanch et al. 2000). PCFs with air holes in a triangular lattice have d and Λ as the air-hole diameter and air-hole spacing, respectively, with varying d/Λ values. In this structure, to study the modal properties of PCF, they considered Λ to be $2.3\ \mu\text{m}$. They validated the fact that polarization corrections are in accordance with that of the vectorial technique, and the scalar solution was found to include wavelengths up to $0.5\ \mu\text{m}$ (Ortigosa-Blanch et al. 2000). The annular core PCFs, different from the typical circular air-holed PCFs, were composed of a solid core with annular-shaped air holes instead of circular ones (Limpert et al. 2003; Uranus and Hoekstra 2004). Furthermore, this structure leads to enhanced polarization effect with minimum and maximum relative errors of $\sim 0.1\%$ and 0.8% , respectively. Unlike the annular-shaped and triangular-shaped air-holed PCFs, the cobweb-structured PCFs have a large air-filling factor (Limpert et al. 2003). During the analysis of modal properties in cobweb-structured PCFs, the authors considered silica glass composition with a core radius of $1\ \mu\text{m}$ and air-hole separation of $\sim 0.12\ \mu\text{m}$. Moreover, the reported scalar solution in cobweb-structured PCFs was a valuable tool for observing their modal properties with a relative error of $\sim 0.05\%–0.8\%$. Further, cobweb-structured PCFs were fabricated by Knight et al. (2000) and analyzed using FEM by Cucinotta et al. (2002). Birefringence achieved by

Aristizabal et al. (2006) and Limpert et al. (2003) was $\sim 2.86 \times 10^{-3}$ at $\lambda = 1.45 \mu\text{m}$, which is in accordance with the result of $\sim 3.27 \times 10^{-3}$ obtained by Saitoh and Koshiba (2005).

Chiang and Wu (2006) reported an octagonal photonic crystal fiber (O-PCF) with eight air holes on the first ring, and it was based on an isosceles triangle with 45° vertex angles. The study was performed using full-wave boundary element method (FW-BEM). They established that O-PCFs can accommodate considerably wider range of wavelengths for single-mode operation than hollow-core photonic crystal fibers (HC-PCFs) and can provide lower confinement loss than HC-PCFs (Chiang and Wu 2006). Simultaneously, Li et al. (2006) reported design and analysis of PCFs for terahertz radiation and obtained terahertz PCFs with flattened dispersion using EIM and the scaling property of Maxwell equations. Li et al. (2007) reported a new and improved EIM for the analysis and design of PCFs. The modal characteristics of the PCFs with guiding cores with one or seven air holes omitted were studied using EIM and compared with those of a typical step index fiber (SIF). The concept of effective core radius and effective refractive index was introduced by Li et al. (2007) utilizing the resemblances between step index fibers (SIFs) and photonic crystal fiber (PCF). Abdelaziz et al. (2010) proposed a new and improved PCF with an elliptical core. The computed effective mode area of the proposed structures was also compared with that of conventional lattice-structured PCF using numerical techniques. Modal parameters such as effective mode area, chromatic dispersion of the fundamental mode, and confinement loss were investigated using full-vector finite element method (FV-FEM) (Abdelaziz et al. 2010). Later, FV-FEM was used to perform a detailed study of large mode area PCFs (LMA-PCF) by incorporating three different angular orientations (Ademgil and Haxha 2011).

They also introduced another novel LMA structure that provides endlessly single-mode operation over a wide range of wavelengths and used FV-FEM technique to evaluate dispersion, confinement loss, and bending loss of the corresponding PCF (Ademgil and Haxha 2012). Using modified structural parameters (or geometrical parameters d and Λ ; see Figure 1.3), one can get an improved effective mode area with endlessly single-mode

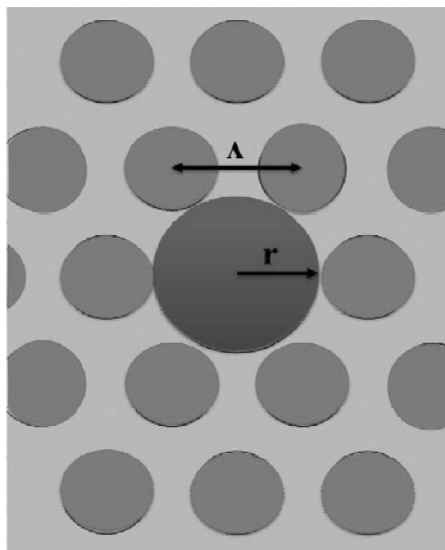


FIGURE 1.3

Cross-sectional view of photonic crystal fiber. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

operation (Ademgil and Haxha 2012). Later, Sharma and Sharma (2013) demonstrated an analytical method to determine the optical performance of single-mode PCF by controlling a significant parameter such as the MFD.

1.4 Mathematical Formulation

The basic formulation of the modal parameter can be described using a V number, which determines the cutoff region between the single-mode and the multimode regions. Besides that, using this basic parameter, one can estimate the modal properties of PCFs based on MFD, effective area (A_{eff}), and dispersion. The fundamental equation that determines the V number of a fiber can be given as follows:

$$V = \frac{2\pi}{\lambda} R \sqrt{n_{co}^2 - n_{cl}^2}. \quad (1.1)$$

In Equation (1.1), n_{co} , n_{cl} , and R are the core, cladding refractive indices, and radius of the core ($\lambda/\sqrt{3}$), respectively for a PCF. The modified expression of V number given by Aristizabal et al. (2006) has been used here:

$$V = \frac{2\pi}{\lambda} R \sqrt{(n_{gl} + \Delta n_d)^2 - (n_{gl} - \Delta n_{gc})^2}. \quad (1.2)$$

Furthermore, a supplementary fitting parameter has been added to the V number, which is given as follows:

$$V\left(\frac{\lambda}{\Lambda}, \frac{d}{\Lambda}\right) = A_1 + \frac{A_2}{1 + A_3 \exp\left(A_4 \frac{\lambda}{\Lambda}\right)} \quad (1.3)$$

The constant terms in Equation (1.3), that is, A_1 , A_2 , A_3 , and A_4 , are defined below:

$$\begin{aligned} A_1 &= 0.55 + 5\left(\frac{d}{\Lambda}\right)^5 - 10.4\left(\frac{d}{\Lambda}\right)^7 + 8.23\left(\frac{d}{\Lambda}\right)^9 \\ A_2 &= 0.71 + 9.7(0.25)^{1.8} + 47.41\left(\frac{d}{\Lambda}\right)^{7.32} - 437.51\left(\frac{d}{\Lambda}\right)^{22.8} \\ A_3 &= 0.17 + 1.86\left(\frac{d}{\Lambda}\right)^{1.7} + 18.97\left(\frac{d}{\Lambda}\right)^{10} - 42.43\left(\frac{d}{\Lambda}\right)^{14} \\ A_4 &= -1.53 + 1.07\left(\frac{d}{\Lambda}\right)^{-0.84} + 1.93\left(\frac{d}{\Lambda}\right)^{1.02} + 3.89\left(\frac{d}{\Lambda}\right)^{13.4} \end{aligned} \quad (1.4)$$

Here, n_{gl} is a refractive index of glass material of the cladding, which is associated with the core index and a difference parameter Δn_d ($\Delta n_d = n_{co} - n_{gl}$ and $\Delta n_{gc} = n_{gl} - n_{cl}$, which

is a function of d/Λ , λ/Λ). The formulation that has been used for Δn_{gc} (Aristizabal et al. 2006) is given by the following:

$$\ln \Delta n_{gc} = c_1 \ln \frac{\lambda}{\Lambda} + c_2 \frac{d}{\Lambda} + c_3 - A. \quad (1.5)$$

1.4.1 Analytical Treatment of Modal Parameter of PCF in Different Material Domains

Several methods are available to design and analyze modal properties of microstructured fibers; however, some methods require high computational skills such as FDTD (Town and Lizier 2001; Qiu 2001), FV-FEM (Limpert et al. 2003), and BPM (Chiang and Wu 2006). The EIM technique is preferred by many researchers due to its flexibility and ease in computation. Because of such ease in computation, the modal properties are analyzed by incorporating distinct structural parameters. We conduct an analytical and procedural analysis of PCFs using the EIM after the mathematical analysis.

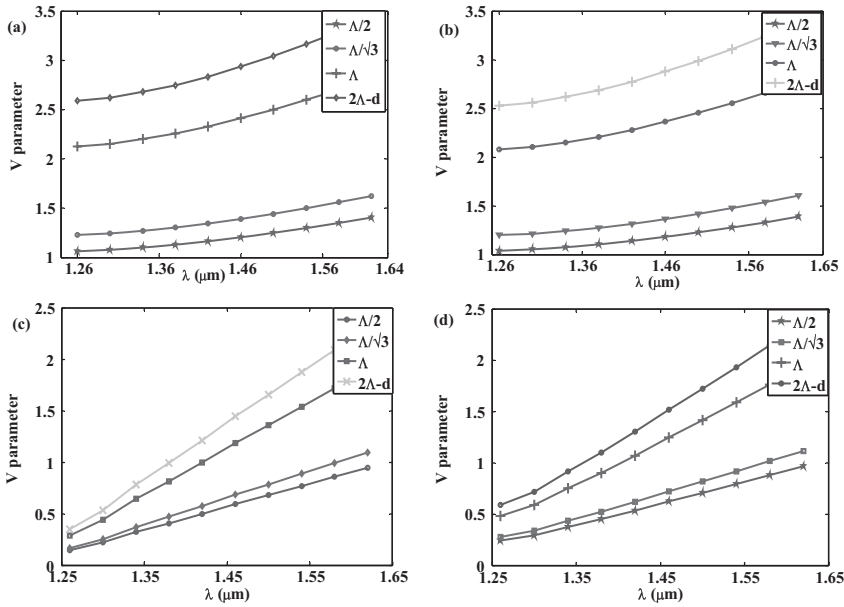
1.5 Results

We have made an extensive study of the modal parameters of crown and phosphate PCFs by varying Λ and R_{eff} using a computationally efficient EIM technique, and the analysis has been done in second and third telecom windows using this technique. With modified structural entities, the modal parameter analysis has been monitored in the context of different material perspectives, which is one of our main objectives. Here, we have calculated the V parameter, MFD, and effective area (A_{eff}) that depict the modal properties of PCF (Lizier and Town 2001).

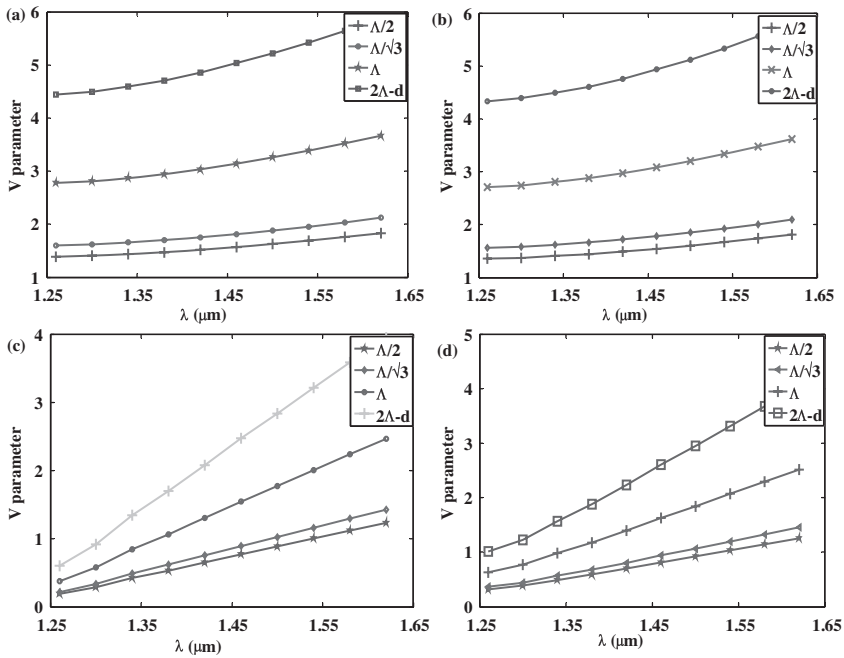
Figures 1.4–1.6 illustrate the variation of the V parameter vs. λ in the range of O to L (in which O and L are the communication band) along with the additional fitting parameter Δn_d reported by Li et al. (2007) and Dudley and Taylor (2009). The fitting parameters include n_{gc} , n_{cl} , n_g , and Δn_d for solving the effective refractive index of PCF. Moreover, we build up our formulation in different material domains. By varying the effective core radii, diameter, and pitches, the corresponding changes were observed. The V parameter is found to develop slowly for the phosphate-based PCF in each set of radii, and it is also found to fall under the multimode region for radius $2\Lambda - d$ with $\Delta n_d = -7 \times 10^{-4}$ and -15×10^{-4} (Dudley and Taylor 2009). In contrast, crown PCF shows a characteristic fall under single-mode region, with a rapid variation within the considered range of wavelength. Moreover, as shown in Figures 1.4–1.6, increase in Λ and R_{eff} shifts PCF toward the multimode region.

This transition to multimode domain is recognized by increase in the number of modes, which is caused by larger pitch values. Meanwhile, crown PCF, in this case, is found to follow a single-mode operation in the lower wavelength region for each set of pitch and effective core radii.

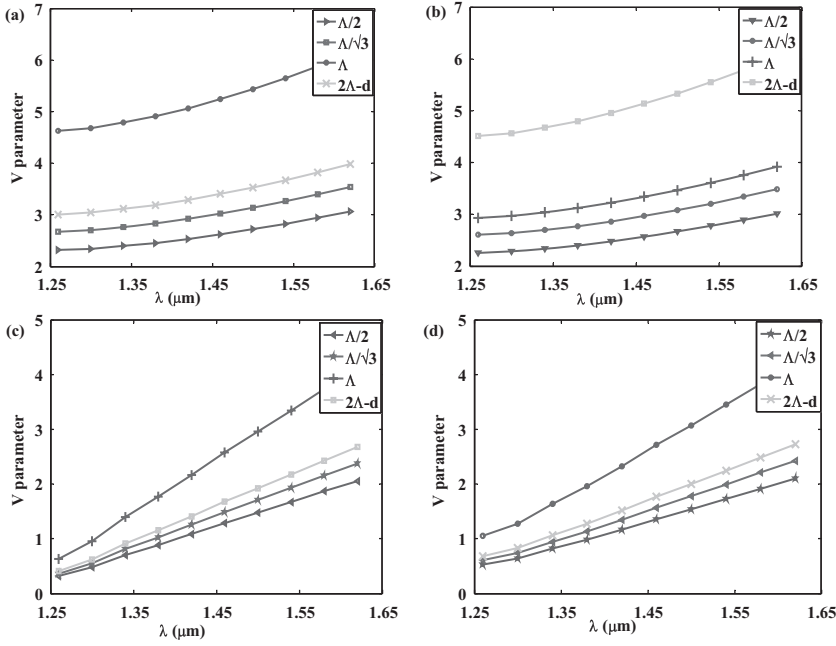
On observing variation in the V parameter with change in geometrical parameters, we attempted to analyze MFD, another important parameter for propagation. MFD is considered as a crucial parameter for super continuum generation, soliton pulse transmission, and optical signal processing (Ortigosa-Blanch et al. 2000; Uranus and Hoekstra 2004). The variation of MFD vs. λ in the band considered for each PCF material has been shown in Figures 1.7–1.9. The value of the parameter is found to increase with increase in effective core radii and pitch. With increase in λ , they show a rapid declining trend in the case of crown PCF, whereas a moderate variation has been observed in the phosphate PCF.

**FIGURE 1.4**

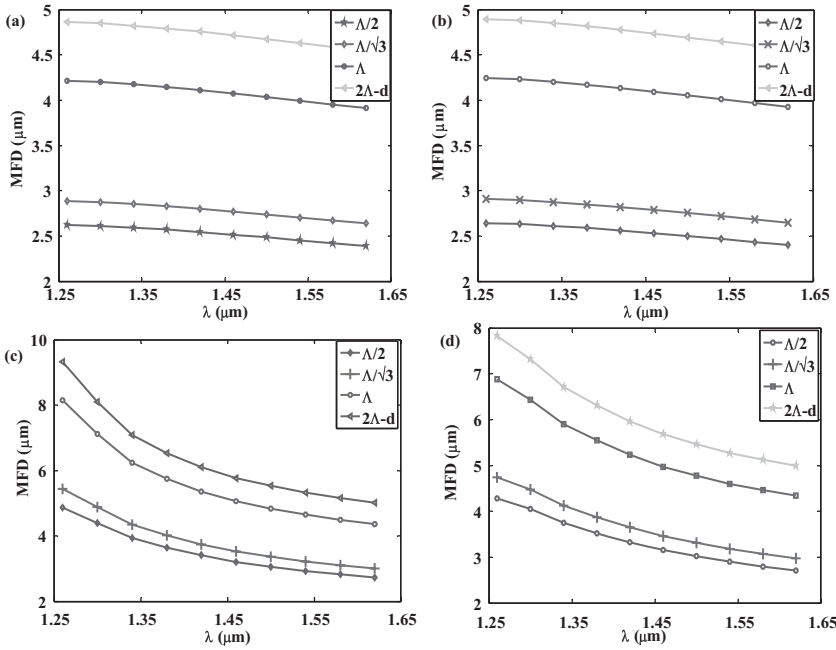
V vs. λ plots at $\Lambda = 2.3 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

**FIGURE 1.5**

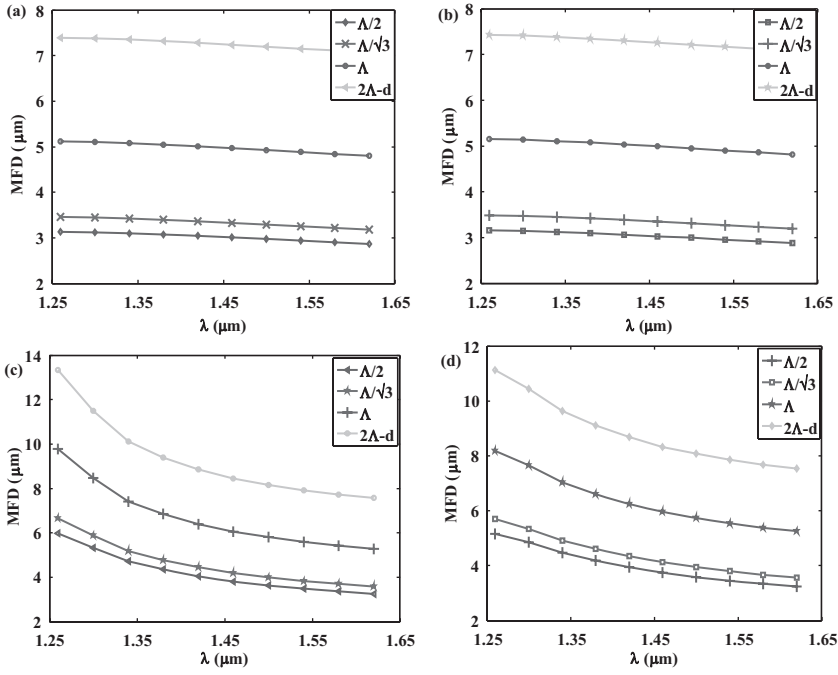
V vs. λ plots at $\Lambda = 3 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

**FIGURE 1.6**

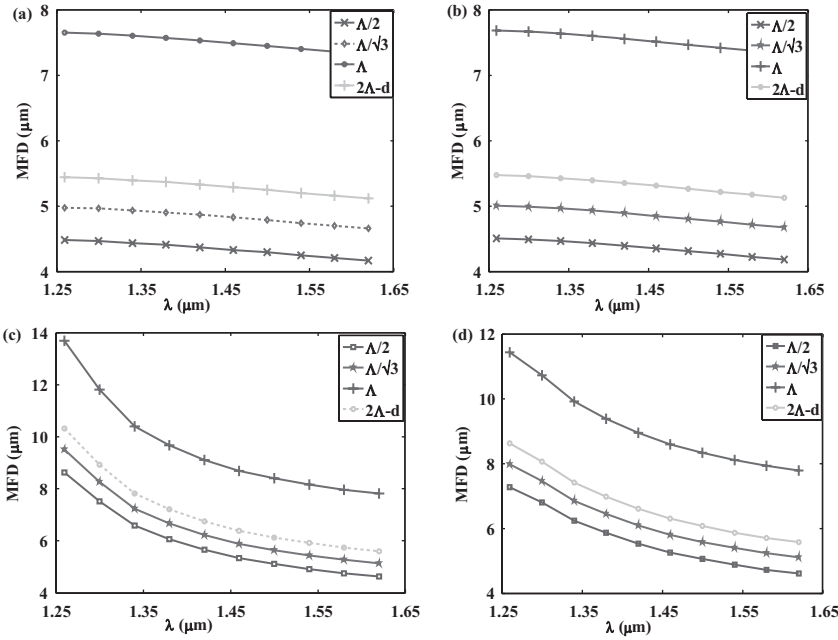
V vs. λ plots at $\Lambda = 6.75 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

**FIGURE 1.7**

MFD vs. λ plots at $\Lambda = 2.3 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown-based PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

**FIGURE 1.8**

MFD vs. λ plots at $\Lambda = 3 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown-based PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

**FIGURE 1.9**

MFD vs. λ plots at $\Lambda = 6.75 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown-based PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

It appears that MFD in both the PCFs decreases on moving toward the higher wavelength region. This trend can be useful for a vast number of practical applications (Knight 2003). It is evident that, with respect to the pattern of MFD vs. λ , crown PCF exhibits an almost exponential decay pattern, whereas phosphate-based PCF yields quite a steady linear decay. Higher values of refractive indices of the cladding and core in crown PCFs may be taken as one of the plausible reasons for this atypical decaying pattern of MFD vs. λ . Moreover, it can be asserted that, with subsequent increase in pitch and core radii, the probability of the confinement of light toward the core decreases and leads to diminution of MFD with respective change in the wavelength band. Furthermore, with increase in the effective core radii (R_{eff}) and Λ , the parameter is found to increase in both the cases.

In addition to the above parameters, the effective area (A_{eff}), as shown in Figures 1.10–1.12, increases in accordance with larger pitch values and effective core radii. However, it shows a declining trend with increase in λ . Further a moderate variation has been observed in case of phosphate-based PCFs, whereas a rapid variation has been seen in crown-based PCFs. Moreover, in each set of PCF the observed values of the variation in the modal parameters are found to increase with increase in pitch and effective core radii.

With increase in λ , the proposed PCFs can work under single-mode operation, and they can be used for other practical applications. The overall changes in modal parameters that have been observed during this study are listed in Table 1.1 and shown in Figure 1.13.

Here, the lowest value for the phosphate- and crown-based PCF is found to be ~ 1.3 and 0.22 , respectively, at $\Lambda = 2.3 \mu\text{m}$. Moreover, MFD of phosphate- and crown-based PCF is found to be ~ 2.8 and $\sim 4.84 \mu\text{m}$ in the E to L band and is found to be ~ 2.82 and $\sim 5.12 \mu\text{m}$ in the L to C band, respectively. In contrast, in the present work, at $\Lambda = 2.3 \mu\text{m}$, the values of MFD are found to be ~ 2.98 and $\sim 5.54 \mu\text{m}$ for phosphate- and crown-based PCF, respectively. In the L to C and E to L bands, the lowest value of effective area was found to be ~ 5.4 and $\sim 5.3 \mu\text{m}^2$ for phosphate-based PCF. The variation of effective area (A_{eff}) with wavelength is found to decrease moderately in the phosphate-based PCF and rapidly in the case

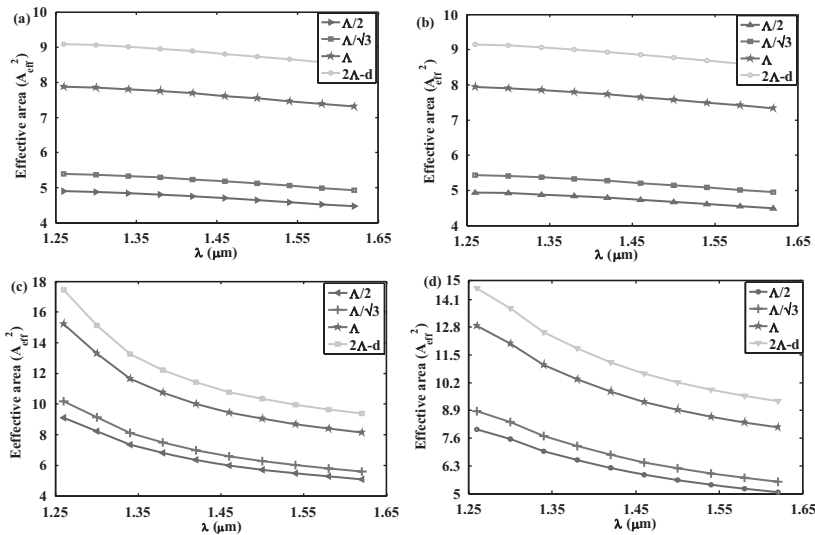


FIGURE 1.10

A_{eff} vs. λ plots at $\Lambda = 2.3 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown-based PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

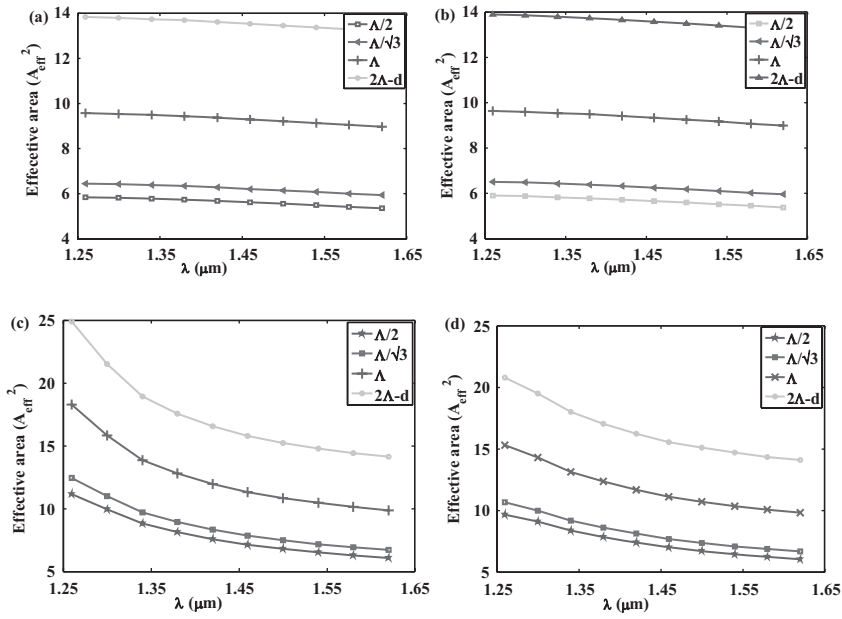


FIGURE 1.11

A_{eff} vs. λ plots at $\Lambda = 3 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown-based PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

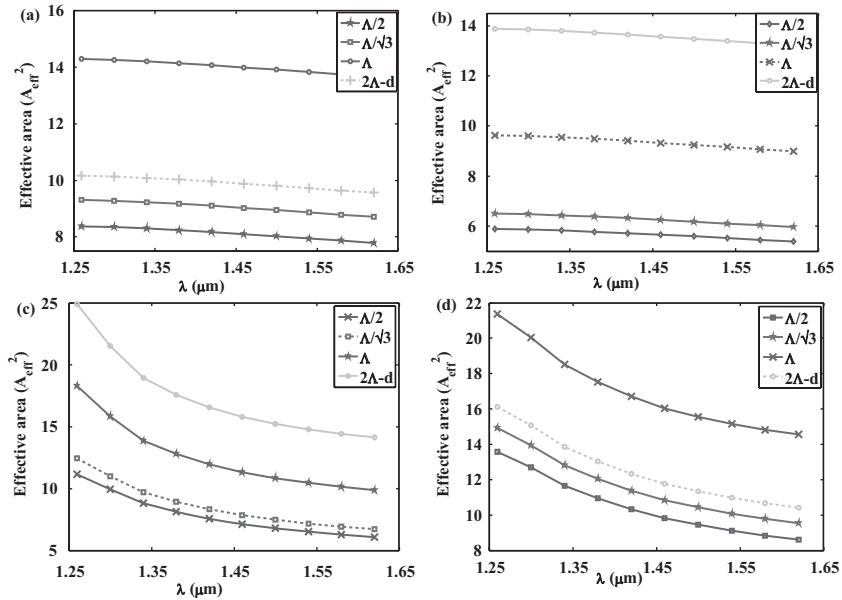


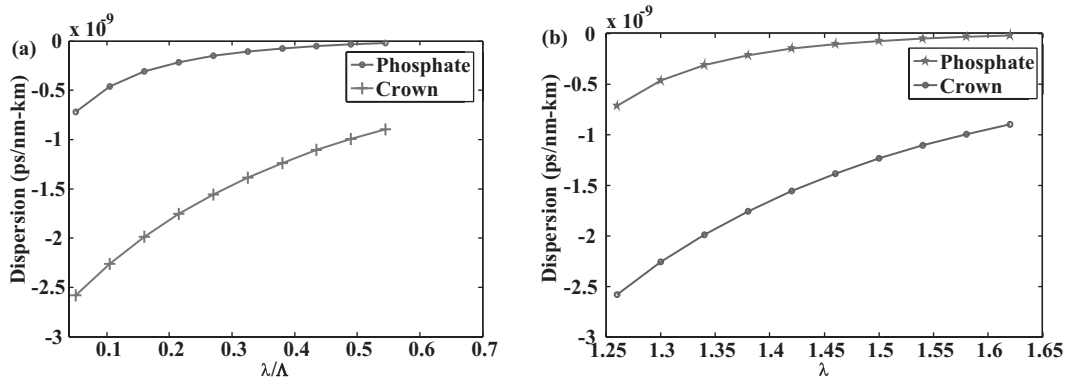
FIGURE 1.12

A_{eff} vs. λ at $\Lambda = 6.75 \mu\text{m}$ when (a) $\Delta n_d = 7 \times 10^{-4}$ and (b) $\Delta n_d = 15 \times 10^{-4}$ for phosphate-based PCF and (c) $\Delta n_d = 7 \times 10^{-4}$ and (d) $\Delta n_d = 15 \times 10^{-4}$ for crown-based PCF. (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

TABLE 1.1

Estimated Values of the Phosphate and Crown-Based PCF

Symbol	Quantity	Material Composition	Pitch	Overall Incremental Value	
				$\Delta n_d = 7 \times 10^{-4}$	$\Delta n_d = 15 \times 10^{-4}$
V	V parameter	Phosphate	2.3	1.53–2.02	1.49–1.99
			3	3.05–4.04	2.98–3.98
			6.75	0.69–0.918	2.26–3.02
		Crown	2.3	0.207–1.36	0.348–1.39
			3	0.413–2.71	0.695–2.77
			6.75	0.094–0.617	0.158–0.629
MFD	Mode field diameter	Phosphate	2.3	2.16–2.24	2.16–2.25
			3	4.19–4.26	4.195–4.27
			6.75	0.963–0.947	0.965–0.948
		Crown	2.3	2.29–4.46	2.28–3.54
			3	4.31–7.36	4.301–5.96
			6.75	0.974–1.68	0.972–1.36
A_{eff}	Effective area	Phosphate	2.3	4.032–4.19	4.039–4.21
			3	7.84–7.97	7.84–7.99
			6.75	1.77–1.799	7.841–7.986
		Crown	2.3	4.28–8.339	4.267–6.624
			3	8.06–13.75	8.04–11.15
			6.75	8.058–13.75	1.816–2.535

**FIGURE 1.13**

Dispersion curves: (a) dispersion vs. λ/Λ and (b) dispersion vs. λ . (From Paul, D. and Biswas, R., *Laser Res. Appl. J.*, 1, 2, 2018.)

of crown-based PCF. The lowest value of phosphate- and crown-based PCF is found to be ~ 5.2 and $10.1 \mu\text{m}^2$ in O to L band at $\Lambda = 2.3 \mu\text{m}$, respectively.

We performed a comprehensive study of the modal parameters in the broader wavelength region and in variable geometrical parameter (Λ , d , and R_{eff}) domains in the context of phosphate and crown materials, and further change in the wavelength range has improved the quality of the proposed microstructured fiber. The attained results

show that the wavelength range has an impact onto the modal parameter. Further, it indicates crown-based PCF to be a better candidate for the future. In addition to that, more control over parameters is observed to be possible in crown-based PCF than in phosphate-based PCF.

1.6 Conclusion

To sum up, a comprehensive analysis of PCFs has been accomplished using EIM in two material domains, namely phosphate and crown within a broad wavelength range (second and third communication bands) in this chapter. Three different air-hole spacings (Λ) and diameters (d) have been considered along with the different effective core radii (R_{eff}) throughout the study. Based on these, all the computed parameters have been studied, and a comparative analysis performed. It has been found that crown-based PCF is preferable to phosphate-based PCF because it accommodates a higher MFD and low beam divergence (Paul and Biswas 2018; Paul et al. 2015a, 2015b). This is indicative of low loss as well. For long-haul communication purposes, PCFs based on both materials offer good standing while surpassing each other in some modal attributes. These results will prove beneficial for experimentalists to design PCFs for long-distance communication purpose. Moreover, the whole work covers the entire telecom window, entailing all possible structural entities; hence, optical engineers can design their fibers according to the requirement based on the established results in this study.

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Transmission Properties of One-Dimensional Photonic Crystal

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2.1 Introduction

The study of periodic structures gains considerable interest, of which the scattering and guiding of waves by one-dimensional (1D) periodic structures play a main role in various applications such as optical engineering, dielectric gratings used in integrated-optics applications, diffraction gratings for beam splitting, grating couplers, linear accelerators, slow-wave structures in microwave tubes, filters, artificial dielectrics, slot arrays, phase-array antennas, frequency-selective structures, and leaky-wave antennas. Many potential applications are found and developed in the area of photonic crystal (PC). PCs are a new class of periodic materials that allow precise control of all electromagnetic (EM) wave properties, with periodical spatial modulation of EM parameters including permittivity, permeability, and conductivity. These mimic a natural crystal with a small and basic building block of atoms or molecules repeated in space. A photonic bandgap (PBG) occurs in a periodic dielectric or metallic media similar to electronic bandgap in a semiconductor crystal. PCs have gained a great attention in research due to their potential ability to control the propagation of light creating a range of forbidden frequency called a PBG. Energized photons found in the bandgap cannot propagate through the medium, which provides the possibility to shape and control the light flow. The simplest PC is a 1D periodic structure that is used as a reference model to understand the formation of the band diagram.

Many researchers investigated the optical properties of 1D PCs (Yablonovitz 1987; John 1987; Born and Wolf 1990; Joannopoulos et al. 2011; Sakoda 2005; Shiveshwari and Mahto 2006). We focus our attention on the resonant transmission (reflection) properties for periodic devices (such as nanostructure arrays and multilayer devices). The method is used with various 1D photonic structures formed by dielectric, plasma, superconductor, meta-material, and so on, which is shown in many literatures (Bendickson et al. 1996; Mittal et al. 2017; Pandey et al. 2013, 2017; Shiveshwari 2011a; 2011b; Shiveshwari and Awasthi, 2015; Shiveshwari and Chakraborty 2012; Shiveshwari 2013; Shiveshwari et al. 2017; Upadhyay et al. 2015a; 2015b, 2016; Yeh 1988; Zhang et al. 2012).

Extensive research on 1D periodic systems has been carried out in quantum context governing the Schrödinger wave equation (Ashcroft and Mermin 1976; Kittel 1986). Ushida et al. (2003) studied using the Bloch wave expansion method, which is valid for an infinite periodic structure as it simplifies the periodic problem and may lead to considerable errors because the number of unit cells in any fabricated system cannot be infinitely large. The experimental and computational investigations focus mainly on wave transmission through a finite structure. The transmission coefficient (TC) remains unexplored from the dispersion relation of the infinite periodic structure, and it is difficult to obtain for comparing the results of experiments even with the knowledge of the band characteristics. However, one can calculate the band characteristics of an infinite structure formed by the periodic repetition of a finite structure. Therefore, currently, the theory of periodic structures holds the primary interest to unveil simple study for the calculation of TC and band structure characteristics. Recently, the transfer matrix method (TMM) has been used to study the 1D periodic structures in which fields at one end of the surface are related to the other surface using a transfer matrix. Transfer matrix for the entire structure is obtained through a transfer matrix of a single period. The general theory for the multilayer structure is shown in [Section 2.2](#). The component $\psi(z)$ satisfies the Helmholtz equation whose solution has been obtained using the TMM. We describe the properties of the transfer matrix and the TC for N periods. The formalism presented here is quite general, and it is used to study any 1D periodic systems. In [Section 2.2.2](#), we obtain transfer matrix for step-index type of periodic structure. [Section 2.2.3](#) gives the study of plasma photonic crystal (PPC). [Section 2.3](#) details the concluding remarks.

2.2 Theoretical Formulation

We begin with the most fundamental equations in electrodynamics called Maxwell's equations, which are given as follows:

$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0 \quad (2.1)$$

$$\vec{\nabla} \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{J} \quad (2.2)$$

$$\vec{\nabla} \cdot \vec{D} = \rho \quad (2.3)$$

$$\vec{\nabla} \cdot \vec{B} = 0, \quad (2.4)$$

where $\vec{E}$ and $\vec{H}$ are the electric field vector (in volts per meter) and magnetic field vector (in amperes per meter), respectively. The quantities $\vec{D}$ and $\vec{B}$ are called electric displacement (in coulombs per square meter) and magnetic induction (in webers per square meter), respectively. The quantities ρ and $\vec{J}$ are the electric charge (in coulombs per cubic meter) and current (in amperes per square meter), densities respectively. EM fields occurring in media in absence of charges are called EM waves. Maxwell's equations are supplemented by material equations:

$$\vec{D} = \varepsilon \vec{E} = \varepsilon_0 \vec{E} + \vec{P} \quad (2.5)$$

and

$$\vec{B} = \mu \vec{H} = \mu_0 \vec{H} + \vec{M} \quad (2.6)$$

where the constitutive parameters ε and μ are tensors of rank 2 and are known as the dielectric tensor (or permittivity tensor) and the permeability tensor, respectively) with $\vec{P}$ and $\vec{M}$ as electric and magnetic polarizations, respectively. The constant ε_0 is called the permittivity of a vacuum and has a value of 8.854×10^{-12} F/m. The constant μ_0 is known as the permeability of a vacuum and has a value of $4\pi \times 10^{-7}$ H/m. Using the mathematical elimination method, we now derive the wave equations in material media, so that each of the field vectors satisfies a differential equation. We set charge density $\rho = 0$ and current density $\vec{J} = 0$. We also assume that the medium is isotropic, so that ε and μ are scalars. Substituting Equation (2.6) in Equation (2.1), we have

$$\vec{\nabla} \times \vec{E} + \mu \frac{\partial \vec{H}}{\partial t} = 0.$$

Dividing by μ and taking curl operator, we obtain

$$\vec{\nabla} \times \frac{1}{\mu} (\vec{\nabla} \times \vec{E}) + \frac{\partial}{\partial t} (\vec{\nabla} \times \vec{H}) = 0. \quad (2.7)$$

Differentiating Equation (2.2) with respect to time and using the material Equation (2.5), we obtain

$$\frac{\partial}{\partial t} (\vec{\nabla} \times \vec{H}) = \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2}. \quad (2.8)$$

Substituting Equation (2.7) in Equation (2.8), we get

$$\vec{\nabla} \times \left(\frac{1}{\mu} \vec{\nabla} \times \vec{E} \right) + \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0. \quad (2.9)$$

We now use the following vector identities:

$$\vec{\nabla} \times \left(\frac{1}{\mu} \vec{\nabla} \times \vec{E} \right) = \frac{1}{\mu} \vec{\nabla} \times (\vec{\nabla} \times \vec{E}) + \vec{\nabla} \left(\frac{1}{\mu} \right) \times (\vec{\nabla} \times \vec{E})$$

and

$$\vec{\nabla} \times (\vec{\nabla} \times \vec{E}) = \vec{\nabla} (\vec{\nabla} \cdot \vec{E}) - \vec{\nabla}^2 \vec{E}.$$

After few mathematical steps, we get

$$\nabla^2 \vec{E} - \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} + (\vec{\nabla} \ln \mu) \times (\vec{\nabla} \times \vec{E}) - \vec{\nabla} (\vec{\nabla} \cdot \vec{E}) = 0 \quad (2.10)$$

Substituting $\vec{D} = \varepsilon \vec{E}$ and applying vector identity,

$$\vec{\nabla} \cdot (\varepsilon \vec{E}) = \varepsilon \vec{\nabla} \cdot \vec{E} + \vec{E} \cdot \vec{\nabla} \varepsilon, \text{ we get}$$

$$\nabla^2 \vec{E} - \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} + (\vec{\nabla} \ln \mu) \times (\vec{\nabla} \times \vec{E}) + \vec{\nabla} (\vec{E} \cdot \vec{\nabla} \ln \varepsilon) = 0 \quad (2.11)$$

This is the wave equation for the field vector $\vec{E}$.

In a similar way, the wave equation for the magnetic field vector $\vec{H}$ can be obtained and is given by the following:

$$\nabla^2 \vec{H} - \mu \varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} + (\vec{\nabla} \ln \varepsilon) \times (\vec{\nabla} \times \vec{H}) + \vec{\nabla} (\vec{H} \cdot \vec{\nabla} \ln \mu) = 0 \quad (2.12)$$

Inside a homogeneous and isotropic medium, the gradient of the logarithm of ε and μ vanishes, and the wave Equations (2.11) and (2.12) reduce to

$$\nabla^2 \vec{E} - \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad (2.13)$$

$$\nabla^2 \vec{H} - \mu \varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} = 0. \quad (2.14)$$

Assuming the whole structure to be homogeneous along the x -axis and periodic along the z -axis, solution of the wave Equations (2.13) and (2.14) can be written as follows:

$$E(z, t) = E(z) e^{i\omega t - \beta x}, \quad (2.15)$$

$$H(z, t) = H(z) e^{i\omega t - \beta x}.$$

where β is the x -component of the wave vector and is known as a propagation constant. For the layered dielectric structure, which consists of homogeneous and isotropic materials, the wave equation is obtained as follows:

$$\left[\frac{d^2}{dz^2} + \left(\frac{\omega^2}{c^2} n^2 - \beta^2 \right) \right] \Psi(z) = 0, \quad (2.16)$$

where ψ stands for E or H .

Therefore, in the generic 1D problem, we solve the Helmholtz wave equation as follows:

$$\frac{d^2\psi(z)}{dz^2} + k^2\psi(z) = 0, \quad (2.17)$$

where

$$i. \quad k = \frac{\sqrt{2m[E - v(z)]}}{\hbar}, \quad (2.18)$$

for an electron moving in a 1D periodic potential.

- ii. For EM wave propagation in 1D periodic layered media, ψ represents the electric field for the case of transverse electric (TE) polarization and magnetic field for the case of transverse magnetic (TM) polarization. Here

$$k = \sqrt{\frac{\omega^2}{c^2} n^2(z) - \beta^2} \quad (2.19)$$

and

$$\beta = \frac{\omega}{c} n \sin \theta. \quad (2.20)$$

n is the refractive index. θ is the ray angle in each layer. Here ω is the wave frequency and c is the speed of light. The two polarizations are identical for normal incidence $\beta = 0$. The general solution in the three regions of [Figure 2.1a](#) can be written as a superposition of right- and left-going waves.

$$\psi(z) = \begin{cases} B_0 e^{ik_b z} + \bar{B}_0 e^{-ik_b z} & \text{if } z < a, \\ \psi_{ab}(z) & \text{if } a < z < b, \\ B_1 e^{ik_b z} + \bar{B}_1 e^{-ik_b z} & \text{if } b < z, \end{cases} \quad (2.21)$$

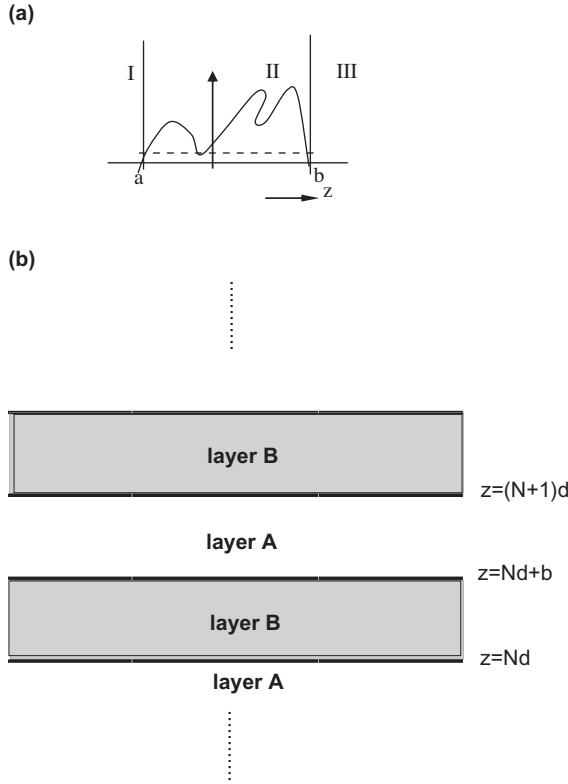
where

$$i. \quad k_b = \frac{\sqrt{2m(E - v_b)}}{\hbar} \quad (2.22)$$

for 1D quantum mechanical scattering problem.

- ii. For 1D PCs, considering $n(z) = n_b$ outside the interval (a, b) ,

$$a. \quad k_b = \sqrt{\frac{\omega^2}{c^2} n_b^2 - \beta^2} \quad (\text{oblique incidence}), \quad (2.23)$$

**FIGURE 2.1**

Scattering from 1D periodic potential. (a) arbitrary potential and (b) step index potential.

We have two separate modes, TE and TM, for this case.

$$b. \quad k_b = \frac{\omega}{c} n_b \text{ (for normal incidence).} \quad (2.24)$$

TE and TM modes are said to be degenerate as $\beta = 0$.

Then, we impose the appropriate boundary conditions at a and b ; typically $\psi(z)$ and its derivatives are continuous; we obtain a pair of linear equations relating the amplitudes in region III ($B_1, \bar{B}_1$) to those in region I ($B_0, \bar{B}_0$). It is more convenient to write these equations in terms of the matrix equation:

$$\begin{pmatrix} B_1 \\ \bar{B}_1 \end{pmatrix} = M \begin{pmatrix} B_0 \\ \bar{B}_0 \end{pmatrix}, \quad (2.25)$$

$$\text{where is a } 2 \times 2 \text{ transfer matrix } M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}. \quad (2.26)$$

Evidently, the TC and reflection coefficient (RC) are, for incidence from left, as follows:

$$T = |t|^2 = \left| \frac{B_1}{B_0} \right|_{\bar{B}_1=0}^2 = \left| \frac{\det M}{M_{22}} \right|^2, \quad (2.27)$$

$$R = |r|^2 = \left| \frac{\bar{B}_0}{B_0} \right|_{\bar{B}_1=0}^2 = \left| \frac{M_{21}}{M_{22}} \right|^2. \quad (2.28)$$

Invariance of Maxwell equations and Schrödinger equation under time reversal symmetry together with energy conservation imposes strong conditions on the structure of transfer matrix M . Let $\psi(z, t)$ be the solution of wave equation, then $\psi^*(z, t)$ will also be a solution, as physical fields are real. And as Maxwell and Schrödinger equations are invariant under time-reversal symmetry, $\psi^*(z, -t)$ is also a solution, that is,

$$\psi^*(z) = \begin{cases} B_0^* e^{-ik_b z} + \bar{B}_0^* e^{ik_b z} & \text{if } z < a, \\ \psi_{ab}^* & \text{if } a < z < b, \\ B_1^* e^{-ik_b z} + \bar{B}_1^* e^{ik_b z} & \text{if } b < z. \end{cases} \quad (2.29)$$

So that the matrix equation becomes

$$\begin{pmatrix} \bar{B}_1^* \\ B_1^* \end{pmatrix} = M \begin{pmatrix} \bar{B}_0^* \\ B_0^* \end{pmatrix}, \quad (2.30)$$

which can be written as

$$\begin{pmatrix} B_1 \\ \bar{B}_1 \end{pmatrix} = \begin{pmatrix} M_{22}^* & M_{21}^* \\ M_{12}^* & M_{11}^* \end{pmatrix} \begin{pmatrix} B_0 \\ \bar{B}_0 \end{pmatrix}. \quad (2.31)$$

Comparing Equations (2.25) and (2.31), we get

$$M_{11} = M_{22}^* \quad M_{21} = M_{12}^*. \quad (2.32)$$

Conservation of energy, time reversal invariance, and inversion under space reflection lead to a special form of matrix M (Merzbacker 1970) with

$$|M_{22}|^2 - |M_{12}|^2 = 1 \quad (2.33)$$

$$\text{or equivalently } \det M = 1. \quad (2.34)$$

We then derive a general expression for the TC, T_N , through a superlattice structure consisting of N unit cells, using the TMM. The two counter-propagating waves in one unit cell ($B_N, \bar{B}_N$) are related to those in the next unit cell ($B_{N+1}, \bar{B}_{N+1}$) by the transfer matrix M as follows:

$$\begin{pmatrix} B_{N+1} \\ \bar{B}_{N+1} \end{pmatrix} = M \begin{pmatrix} B_N \\ \bar{B}_N \end{pmatrix}. \quad (2.35)$$

The total TM for the entire structure is obtained by an iterative way because every period in this superlattice structure has the same transfer matrix. Therefore, the matrix equation becomes

$$\begin{pmatrix} B_{N+1} \\ \bar{B}_{N+1} \end{pmatrix} = M^N \begin{pmatrix} B_0 \\ \bar{B}_0 \end{pmatrix}, \quad (2.36)$$

and the TC, T_N , is given by

$$T_N = \left| \frac{1}{M_{22}^N} \right|^2. \quad (2.37)$$

The N^{th} power of a unimodular 2×2 transfer matrix can be obtained in several ways such as using the Cayley–Hamilton's theorem, which says that every matrix satisfies its own eigen value equation; by induction method; and using the Cauchy integral formula for matrices. We follow the diagonalization process of matrices. We use the identity

$$\left\{ S^{-1} \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} S \right\}^N = S^{-1} \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}^N S, \quad (2.38)$$

where S can be found, such that

$$S^{-1} \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} S = \begin{pmatrix} e^{i\varphi} & 0 \\ 0 & e^{-i\varphi} \end{pmatrix}. \quad (2.39)$$

$e^{\pm i\varphi}$ are the eigen values, and the diagonalizing matrix S is just the matrix whose column vectors are the eigen vectors of the matrix M .

Taking N th power of Equation (2.39) and using Equation (2.38), we get

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}^N = S \begin{pmatrix} e^{iN\varphi} & 0 \\ 0 & e^{-iN\varphi} \end{pmatrix} S^{-1} = \begin{pmatrix} M_{11}U_{N-1} - U_{N-2} & M_{12}U_{N-1} \\ M_{21}U_{N-1} & M_{22}U_{N-1} - U_{N-2} \end{pmatrix}. \quad (2.40)$$

that is, the elements of the matrix M^N can be expressed in terms of the matrix M as

$$M^N = MU_{N-1} - IU_{N-2}, \quad (2.41)$$

where $U_N = \frac{\sin(N+1)\phi}{\sin\phi}$ is the Chebyshev polynomial (Abramowitz and Stegun 1972) of second kind and I is a 2×2 identity matrix; ϕ is the Bloch phase for a single period, and it depends on the eigen values of the matrix M as

$$e^{i\varphi} = \lambda_1 = \lambda_2^{-1} = \frac{1}{2} \text{Tr}(M) + \left\{ \left[\frac{1}{2} \text{Tr}(M) \right]^2 - 1 \right\}^{1/2}, \quad (2.42)$$

where $\lambda_{1,2}$ are the eigen values of the matrix M and $\lambda_1 = \lambda_2^{-1}$ because the matrix is unimodular, and $\cos\phi = \frac{1}{2} \text{Tr}(M) = \text{Re}(M_{22}) = \text{Re}(\frac{1}{t})$.

From Equations (2.37) and (2.41),

$$T_N = \frac{1}{|M_{22}U_{N-1} - U_{N-2}|^2}. \quad (2.43)$$

Using the recurrence relation $2 \cos \phi U_{N-1} - U_{N-2} = U_N$, we get

$$T_N = \left[1 + U_{N-1}^2 \left(\frac{1}{T_1} - 1 \right) \right]^{-1} \quad (2.44)$$

$$= \left[1 + \frac{\sin^2 N \phi}{\sin^2 \phi} \left(\frac{1}{T_1} - 1 \right) \right]^{-1}. \quad (2.45)$$

T_1 corresponds to the TC through a single unit cell. Equation (2.45) is the general expression for T_N valid for any arbitrary 1D periodic structure. It can be used to study the multiple bend quantum wires (Wu and Sprung et al. 1993), which are dominated by their 1D nature in low energy regions.

2.2.1 Properties of TC

We recapitulate some of the properties related to T_N :

- i. The value of T_N shows resonant behavior when the transmission through the basic subunit of the system is unity.
- ii. T_N is a rapidly fluctuating function of the Bloch phase ϕ , when it is real. There are $(N-1)$ transparent points of T_N in any allowed region in addition to $T_1 = 1$, whenever $T_1 = 0$, we have $T_N = 0$.
- iii. $T_N = 1$ for $\text{Tr}(M) = 0$, for all even number of periods.

The well-known Chebyshev polynomial of second kind has the following properties:

$$U_{-1}(\cos \phi) = 0.$$

$$U_0(\cos \phi) = 1.$$

$$U_1 = 2 \cos \phi.$$

$$U_2 = 4 \cos^2 \phi - 1.$$

$$U_3 = 8 \cos^3 \phi - 4 \cos \phi.$$

$$U_4 = 16 \cos^4 \phi - 12 \cos^2 \phi + 1.$$

$$U_5 = 32 \cos^5 \phi - 32 \cos^3 \phi + 6 \cos \phi.$$

$$U_6 = 64 \cos^6 \phi - 80 \cos^4 \phi + 24 \cos^2 \phi - 1.$$

If $\cos \phi = 0$, we have

$$U_1 = U_3 = U_5 = 0, \text{ or we can say that}$$

$$T_2 = T_4 = T_6 = \dots = T_{N(\text{even})} = 0.$$

- iv. We can calculate the band structure of an infinite superlattice structure formed by the periodic repetition of the finite structure by evaluating the frequencies of unit transmission through a finite structure.

For an infinite periodic structure, we have

$$\psi(z + d) = \psi(z) e^{ikd}, \quad (2.46)$$

where k , the Bloch wave vector, satisfies the relation

$$\det (M_{ij} - \delta_{ij} e^{ikd}) = 0. \quad (2.47)$$

M_{ij} is the $(ij)^{\text{th}}$ element of the matrix M describing one period, δ_{ij} is the Kronecker delta function, d is the period, and e^{ikd} is also the eigen value of M similar to $e^{i\phi}$. Therefore,

$$e^{ikd} = e^{i\phi}$$

or

$$kd = \phi + 2m\pi, \quad (2.48)$$

Therefore, whenever $k = \pm \frac{m\pi}{Nd}$, the quantity $\phi = \pm \frac{m\pi}{N}$. Thus, the frequencies (energies) corresponding to $k = \pm \frac{m\pi}{Nd}$ are the frequencies (energies) corresponding $\phi = \pm \frac{m\pi}{N}$, which, in turn, are the frequencies (energies) corresponding to unity transmission through the finite repeated structure with N periods. $\cos kd = \frac{1}{2} \text{Tr}(M) = \text{Re}(\frac{1}{2})$ gives the dispersion relation for an infinite periodic structure. It elucidates the band structure characteristics. If $|\text{Tr}(M)| > 2$, the wave vector must be purely imaginary that corresponds to the forbidden band of the structure. $|\text{Tr}(M)| < 2$ permits k to be real, which corresponds to the allowed band of the infinite structure. The values of the wave vector for which $|\text{Tr}(M)| = 2$ correspond to the edges between the allowed bands and the forbidden bands.

- v. In the gap region, we see an exponential variation in TC, T_N that is, when $\phi = \pi + i\theta$,

$$T_N = \left[1 + \frac{\sin h^2 N \theta}{\sin h^2 \theta} \left(\frac{1}{T_1} - 1 \right) \right]^{-1}. \quad (2.49)$$

- vi. When $N\phi$ is odd multiples of $\pi/2$, that is, when $N\phi = (2m + 1)\pi/2$, $\sin^2 N\phi$ takes the maximum value one. We will have a minimum T_N at this point as this is the most rapidly varying term:

$$T_N = \left[1 + \frac{1}{\sin^2 (2m+1) \frac{\pi}{2N}} \left(\frac{1}{T_1} - 1 \right) \right]^{-1}. \quad (2.50)$$

2.2.2 Transfer Matrix for the Step Index Structure

We now determine the explicit form of the matrix assuming a Kronig–Penney slab consisting of alternate layers of materials *A* and *B* having refractive indices n_a and n_b (potential v_a and v_b for electronic case) and thicknesses a and b , respectively, as shown in [Figure 2.1b](#), that is,

$$n(z) = n_b + (n_a - n_b) \sum_N \theta[z - (Nd + b)] \quad (2.51)$$

or

$$v(z) = v_b + (v_a - v_b) \sum_N \theta[z - (Nd + b)]$$

and

$$\theta(z) = \begin{cases} 1, & z > 0 \\ 0, & z < 0. \end{cases} \quad (2.52)$$

We start with a situation such that the modal fields are described by oscillatory nature in layer *B* and evanescent nature in layer *A*.

$\psi(z)$, for the N^{th} unit cell, can be written as follows:

$$\Psi(z) = \begin{cases} B_N e^{ik_b \{z - (Nd + b)\}} + \bar{B}_N e^{-ik_b \{z - (Nd + b)\}}, \\ A_N e^{k_a \{z - (N+1)d\}} + \bar{A}_N e^{-k_a \{z - (N+1)d\}}, \end{cases} \quad (2.53)$$

where k_b s are given by Equations (2.22 through 2.24),

$$\text{and } k_a = \sqrt{\beta^2 - \frac{\omega^2}{c^2} n_a^2} \text{ for 1D PCs and}$$

$$k_a = \frac{\sqrt{2m(v_a - E)}}{\hbar}, \text{ for electronic case.} \quad (2.54)$$

Continuity conditions at $z = Nd + b$ and $z = (N + 1)d$ give the matrix Equation (2.35), where

$$M_{11} = e^{ik_b b} \left[\cos h k_a a - \frac{i}{2} \left(\eta - \frac{1}{\eta} \right) \sin h k_a a \right] = M_{22}^*, \quad (2.55)$$

$$M_{12} = -\frac{i}{2} e^{ik_b b} \left(\eta + \frac{1}{\eta} \right) \sin h k_a a = M_{21}^*, \quad (2.56)$$

$$\phi = \cos^{-1} \left[\cos h k_a a \cos k_b b + \frac{1}{2} \left(\eta - \frac{1}{\eta} \right) \sin h k_a a \sin k_b b \right], \text{ and} \quad (2.57)$$

$$T_1 = \left[1 + \frac{1}{4} \left(\eta + \frac{1}{\eta} \right)^2 \sin^2 h^2 k_a a \right]^{-1}, \quad (2.58)$$

For 1D PCs, $\eta = k_a/k_b$ for TE modes and $\eta = k_a/k_b \cdot n_b^2/n_a^2$ for TM modes, it is different due to the continuity conditions at the boundary. By increasing the frequency (energy), a critical frequency (energy) is obtained beyond which the modal fields are characterized by oscillatory nature in both the layers, that is, k_a becomes ik_a in all the expressions. For TM waves incident at the Brewster's angle, there is complete transmittance irrespective of the geometrical parameters of the structure. Under this condition, the photonic band equation and the expression for T_1 become

$$\phi = \cos^{-1} \left[\cos k_a a \cos k_b b - \frac{1}{2} \left(\frac{n_b}{n_a} + \frac{n_a}{n_b} \right) \sin k_a a \sin k_b b \right], \quad (2.59)$$

and

$$T_1 = \left[1 + \frac{1}{4} \left(\frac{n_a}{n_b} - \frac{n_b}{n_a} \right)^2 \sin^2 k_a a \right]^{-1}, \quad (2.60)$$

where $k_a = \omega/c n_a$ and $k_b = \omega/c n_b$.

2.2.3 1D Plasma Photonic Crystal

PCs can generate spectral regions called PBGs within which the propagation of EM wave is absolutely forbidden. This novel property provides a wide platform for many applications in photonic devices, such as dielectric mirrors, fabry perot filters, distributed feedback lasers, super narrow filter, phase adjuster, fiber waveguide, polarization filters, and splitters. 1D PC is the simplest version of a PBG material and has been studied in many literatures (Awasthi et al. 2006, 2009, 2011, 2017; Kumar and Ojha 2008; Shiveshwari and Mahto 2006; Shiveshwari and Chakraborty 2012; Shiveshwari et al. 2017; Wang et al. 2018), which has many advantages such as relatively easy, cheap, and amenable fabrication compared with 2D or 3D PCs. Active terahertz waveform synthesis is possible (Gingras and Cooke 2017) for a broad range of applications including high-speed wireless communications, using periodic 1D arrays, creating frequency combs that are completely tunable in frequency, bandwidth, amplitude, and chirp.

Past decades have witnessed that PBG structures have been constructed from almost every available natural material. Recently, metal dielectric PCs have evoked much interest due to its various applications, and a novel class of PBG structures containing metamaterials has also attracted much attention. Metamaterials, first explored by Veselago (1968), have attracted much attention with regard to their experimental realization by Shelby et al. (2001) and fabrication by Pendry (2000, 2003), which are artificial materials showing EM properties unlike conventional naturally occurring materials. They include double-negative (DNG) and single-negative (SNG) materials. The former possesses a frequency window where the effective permittivity and permeability are simultaneously negative, whereas the latter consists of ϵ -negative materials (ENG) with $\epsilon < 0$ but $\mu > 0$ and μ -negative materials (MNG) with $\mu < 0$ and $\epsilon > 0$. Applications of metamaterials (Smith et al. 2004; Shalaev 2007) include the development of a super lens, antennas with superior properties, optical nanolithography and nanocavities, and meta coatings that

can make objects invisible. The transmission properties of 1D dielectric–semiconductor metamaterial PC (Aly et al. 2017) have been studied at terahertz (THz) range theoretically. This research area has been extended to plasma dielectric PCs (Guo 2013; Hojo and Mase 2004; Dixit and Pandey 2017; Prasad et al. 2013; Li et al. 2018; Shiveshwari and Mahto 2006; Wen et al. 2017; Zhang 2018) and is expected to obtain many new significant characteristics. Plasma is very dispersive throughout the spectrum, and EM wave with frequency below the plasma frequency cannot propagate through bulk plasma. However, it is possible for EM wave to be guided below the plasma frequency when dielectric materials are periodically introduced. The plasma dielectric PCs expand their wide use in plasma function devices such as plasma lens, plasma antenna, plasma stealth aircrafts, and frequency filters. Few works on PCs focused mainly on the normal incidence EM wave propagation; however, for many applications, a PBG is highly desirable for all propagation directions and polarizations (termed as a complete PBG). Thus, the search for 1D PCs with complete PBGs for all polarizations is of great significance.

In this chapter, we study the propagation of EM wave through 1D plasma dielectric PC, a multilayer structure containing alternating thin plasma slabs and conventional dielectric medium, using the TMM. The plasma layer has permittivity following a negative permittivity metamaterial like dispersion. Here, we show that a new band or gap corresponding to $\omega = \omega_p$ occurs only for TM-polarized waves, due to which plasma dielectric PC functions as a polarization splitter. These new bands or gaps disappear for the particular case of propagation along the stratification direction. As the conventional PBG develops from the interference of Bragg scattering due to the periodicity of the dielectric structures, material dispersion does not play a crucial role in their appearance. The plasma dispersion, and not the interference, plays a key role in the formation of new band or gap near $\omega = \omega_p$. We study the dependence and variation of the TC and PBG characteristics with the

1. Number of unit cells,
2. Plasma density,
3. Angle of incidence,
4. Plasma layer width, dielectric layer width, and
5. Dielectric constant of the dielectric medium

for both TE and TM polarizations. The problem gains interest because the band characteristics in plasma dielectric PCs are evident even when the number of unit cells (N) is quite small. These features have been discussed for $N = 2, 3, 5, 50$, and ∞ . For infinite 1D plasma PC, that is for $N \rightarrow \infty$, the dispersion relation analogous to classic Kronig–Penny model has been obtained. We study the transmission properties in a few- N system and show the existence of gaps and transmission bands even for $N = 2$ system. Resonance transmission bands have important applications in optical filtering with super narrow transmission bands.

We start with one dimensional wave equation given by Equation (2.16) to study the wave propagation in 1D plasma dielectric PC composed of N unit cells, that is, N alternate layers of plasma and dielectric materials of thicknesses “ a ” and “ b ,” respectively, as shown in Figure 2.1. Thus the multilayer has a period $d = a + b$, $\epsilon(z)$, which is the permittivity of the structure given by

$$\varepsilon(z) = \begin{cases} \varepsilon_b, & \text{for } Nd < z < Nd + b \\ \varepsilon_a = 1 - \frac{\omega_p^2}{\omega^2}, & \text{for } Nd + b < z < (N + 1)d. \end{cases} \quad (2.61)$$

The multilayer composite is embedded in a medium identical to the dielectric layer. The quantity β is real, which represents the parallel component of the wave vector and consequently is conserved throughout the multilayer. However, based on the incident angle and the values of ε_a , the normal component of the wave vector in plasma layer can be real or purely imaginary. Here ω is the wave frequency and c is the speed of light.

$$\omega_p = \frac{e^2 n_p}{\varepsilon_0 m} \quad (2.62)$$

is the plasma frequency with n_p as electron density. We consider x to represent the lateral direction and z to represent the stacking direction. We have studied both TE and TM polarizations separately. For normal incidence, the two polarizations are identical.

$\psi(z)$, for the N^{th} unit cell, can be written as Equation (2.53) (for $\omega < \omega_p$).

$$\begin{aligned} \text{Here, } k_b &= \frac{\omega}{c} \sqrt{\varepsilon_b} \\ \text{and } k_a &= \frac{\omega}{c} \sqrt{\frac{\omega_p^2}{\omega^2} - 1} \end{aligned} \quad (2.63)$$

as the parallel component of the wave vector $\beta = 0$.

By increasing the frequency, a stage is obtained where $\omega = \omega_p$ beyond which the modal fields are characterized by oscillatory nature in both layers, that is, k_a becomes ik_a in all the expressions, where $k_a = \frac{\omega}{c} \sqrt{1 - \omega_p^2 / \omega^2}$.

For the two-layered periodic structure, the dispersion relation is obtained according to Bloch–Floquet theorem, which is directly related to the trace of the transfer matrix M for infinite periodic structure as follows:

$$\cos kd = \frac{1}{2} \text{Tr}(M) = \left[\cos hk_a a \cos k_b b + \frac{1}{2} \left(\frac{k_a}{k_b} - \frac{k_b}{k_a} \right) \sin hk_a a \sin k_b b \right], \text{ for } \omega < \omega_p \quad (2.64)$$

and

$$\cos kd = \left[\cos k_a a \cos k_b b - \frac{1}{2} \left(\frac{k_a}{k_b} + \frac{k_b}{k_a} \right) \sin k_a a \sin k_b b \right], \text{ for } \omega > \omega_p, \quad (2.65)$$

where k is the Bloch wave vector. For oblique incidence, $\beta \neq 0$.

$$\cos kd = \cos k_a a \cos k_b b - \frac{1}{2} \left(\eta + \frac{1}{\eta} \right) \sin k_a a \sin k_b b \quad (2.66)$$

$$\text{where } k_b = \left[\frac{\omega^2}{c^2} \varepsilon_b - \beta^2 \right]^{1/2} \quad (2.67)$$

$$\text{and } k_a = \left[\frac{\omega^2}{c^2} \left(1 - \frac{\omega_p^2}{\omega^2} \right) - \beta^2 \right]^{1/2}. \quad (2.68)$$

Bloch wave vector k is obtained from the eigen values of the transfer matrix corresponding to one unit cell. k can be real or imaginary corresponding to the propagating or evanescent waves. Equation (2.66) holds for both TE and TM polarizations. The only difference is in the parameter η

$$\eta = \begin{cases} \frac{k_a}{k_b} & \text{for TE mode} \\ \frac{k_a \varepsilon_b}{k_b \varepsilon_a} & \text{for TM mode} \end{cases}. \quad (2.69)$$

For normal incidence ($\beta = 0$), at $\omega = \omega_p$, $\varepsilon_a \rightarrow 0$, $k_a \rightarrow 0$, and Equation (2.66), for both TE and TM polarizations, adopts the nonsingular form as

$$\cos kd \approx \cos k_b b - \frac{1}{2} \frac{\omega}{c} \sqrt{\varepsilon_b} a \sin k_b b. \quad (2.70)$$

This can take any real value either inside or outside the interval $[-1, 1]$. For oblique incidence, ($\beta \neq 0$), at $\omega = \omega_p$, $\varepsilon_a \rightarrow 0$, $k_a \rightarrow \pm i\beta$, and the second term in the right-hand side of Equation (2.66) remains singular for TM polarization.

2.3 Results and Discussion

In this section, transmission and RCs have been calculated for 1D plasma dielectric PCs from which the condition for complete transmission is deduced for TE and TM polarizations. We study the dependence and variation of the TC and PBG characteristics with different parameters for finite and infinite PCs by knowing T_1 and ϕ .

2.3.1 Variations of TC and PBG with Number of Unit Cells (N)

Figures 2.2 and 2.3 show the variation of PBG characteristics with number of unit cells. Using the expression for TC, all dielectric photonic structures have been studied in Figure 2.2 for wave propagation normal to the periodic layers. Dielectric parameters are $\varepsilon_b = 1$ (air) and $\varepsilon(z) = 12.25$ (Al_2O_3) for dielectric material. $b = 2.9a$, a and b being the thicknesses of the dielectric material and air, respectively. In Figure 2.3, we take $b = 2a$ and $\omega_p = 2c/a$ to study the dependence of TC on N for 1D binary plasma dielectric PC for normal incidence.

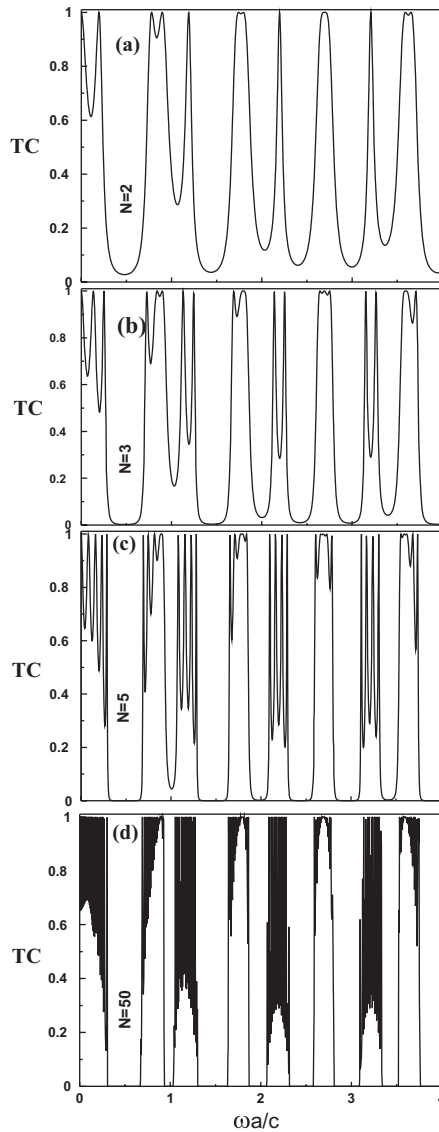
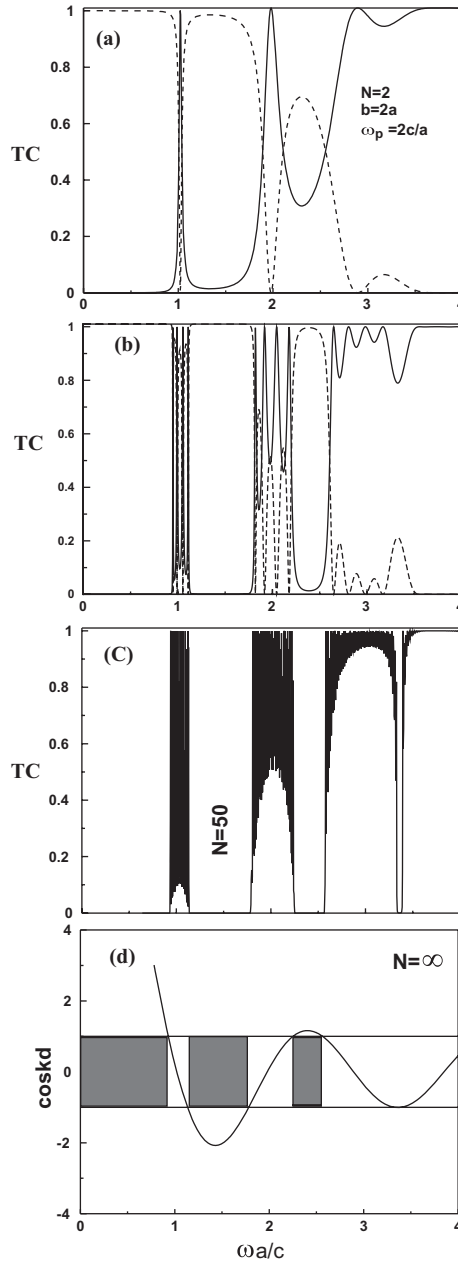


FIGURE 2.2

Plot of TC versus $\omega a/c$ for wave propagation along the periodic axis for dielectric PC. (a) $N = 2$, (b) $N = 3$, (c) $N = 5$ and (d) $N = 50$ (From Shiveshwari, L. and Mahto, P., *Solid State Commun.*, 138, 160–164, 2006.)

We plot the TC for $N = 2, 5$, and 50 , as well as the Bloch phase. In [Figure 2.3a](#) and [b](#), dotted lines represent the RC. We obtain negligible transmittance even for an $N = 2$ system, showing that the emerging band structure is evident with surprisingly few layers. Each of the allowed regions, that is, $|\cos \phi| < 1$, gives $(N-1)$ transmission peaks in addition to $T_1 = 1$. Such regions are separated by distinct valleys where $|\cos \phi| > 1$ and TC approaches negligible values. The quantity $\cos \phi$ determines the band structure of 1D PC. In the gap region, ϕ has an imaginary part; therefore, the Bloch wave is evanescent; the dispersion relation has no real solution for ϕ , which corresponds to the bandgap of

**FIGURE 2.3**

Plot of TC for (a) $N = 2$, (b) $N = 5$, (c) $N = 50$ and (d) dispersion relation versus $\omega a/c$ for wave propagation along the periodic axis for PPC. (From Shiveshwari, L. and Mahto, P., *Solid State Commun.*, 138, 160–164, 2006.)

the 1D PC. In the allowed region, ϕ takes real value, and this leads to propagating Bloch waves. The band edges are the region where $|\cos \phi| = 1$. It is clear from Figures 2.2 and 2.3 that a particular valley gets flatter and deeper as N increases. It is obvious that TC becomes independent of N for large values of N , and the locations of the multichannel peaks of TC are in the allowed band of the infinite structure. TC has the general feature,

that is, the appearance of frequency bands in which TC is close to 1 separated by increasing distinct valleys where TC approaches zero for large N . These figures show that more layer repeats are required to achieve deep transmission minima. The dispersion relation for $N = \infty$ has been shown below the plots of TC. TC gives $(N-1)$ maxima in addition to $T_1 = 1$ in the regions where $|\cos kd| < 1$, which corresponds to the allowed frequency band. The regions for which $|\cos kd| > 1$ correspond to the forbidden frequency gaps (shaded region) for infinite structure where TC approaches negligibly small values.

2.3.2 Variations of TC and PBG with Plasma Density

Variation of PBG with plasma density has been shown in Figure 2.4 for 1D binary plasma dielectric PC with $a = b$ at normal incidence. We notice that the width of the gap region

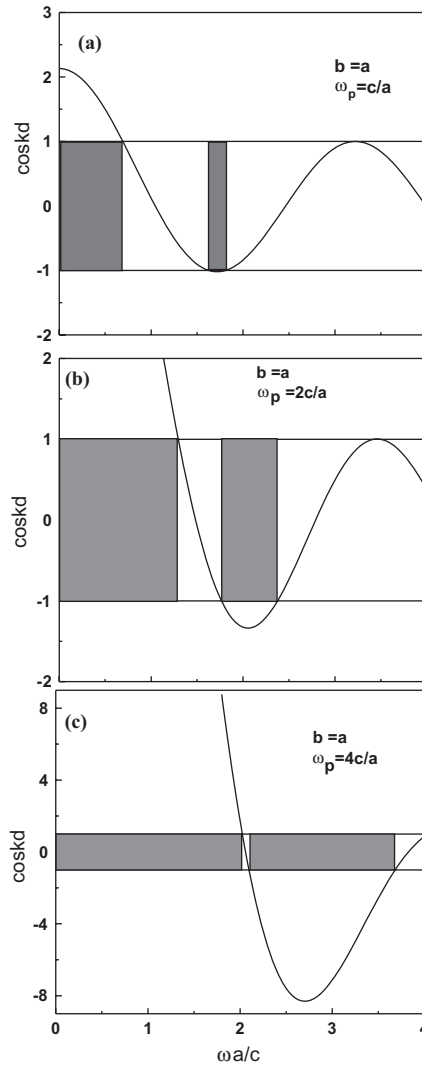


FIGURE 2.4

Plot of dispersion relation versus $\omega a/c$ for $a = b$ and (a) $\omega_p = c/a$, (b) $\omega_p = 2c/a$, and (c) $\omega_p = 4c/a$. (From Shiveshwari, L. and Mahto, P., *Solid State Commun.*, 138, 160–164, 2006.)

increases with increase in plasma density. The band edges of the gap shift toward the higher frequency with increasing plasma density. Similar shift and enlargement of gap region have been observed earlier as well (Li et al. 2003).

2.3.3 Variations of TC and PBG with Angle of Incidence

The dependence of TC and PBG characteristics of 1D plasma dielectric PC with angle of incidence has been shown in Figures 2.5–2.8. The projected photonic band structure over the in-plane wave vector β has been examined for an arbitrary direction of propagation. The projected PBS plays a role in determining a 1D plasma dielectric PC with or without PBG. The projected PBS corresponding to $a = b = 2c / \omega_p, \epsilon_b = 1.0$ is shown in Figure 2.5. White regions in Figures 2.5 and 2.6 indicate the forbidden bands where there are no EM modes. There is a new band near $\omega = \omega_p$ for TM polarization whose width increases with the wave vector, β , that is, with the angle of incidence. In Figure 2.6, we change the layer thickness $b = c/\omega_p$. Instead of band near $\omega = \omega_p$, we observe a gap that is distinct from Bragg gap, which is a characteristic of TM polarization and is produced by strong dispersive character of plasma. The new band or gap near $\omega = \omega_p$ develops only for TM polarization, that is, for incidence angles other than normal incidence and its width increases with increasing angle of incidence. In Figure 2.7, we increase the plasma density to $\omega_p a / c = 4.0$ to plot the TC versus frequency for $N = 2$ PC. The frequency gap becomes larger with the increase of plasma density. Figure 2.7a gives the band characteristics for normal incidence. Figure 2.7b is for oblique incidence, ($\beta = 0.4 \omega_p / c$). The high transmission shown in

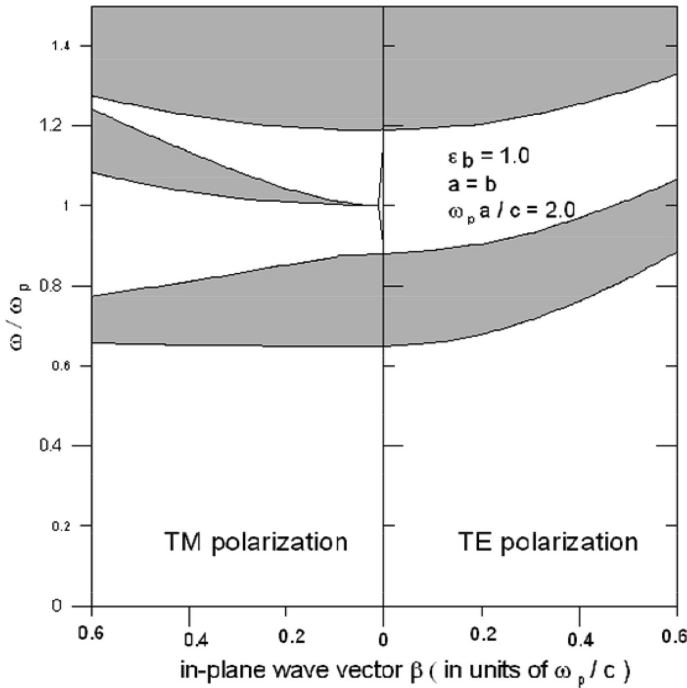
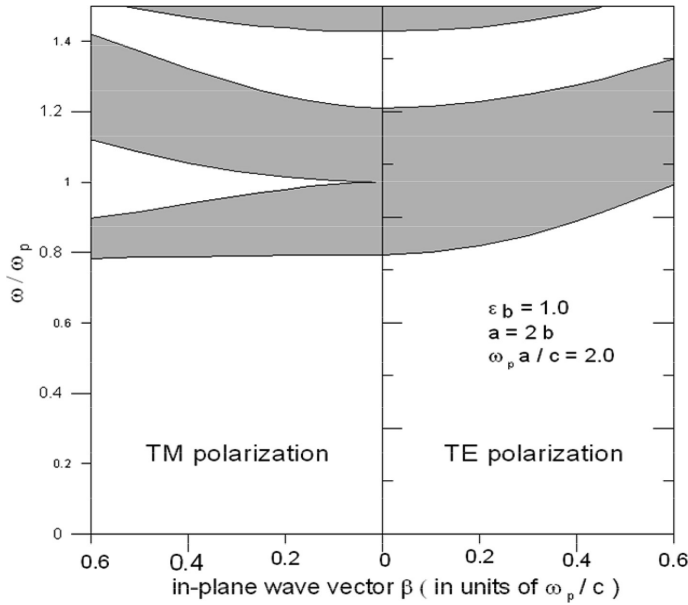
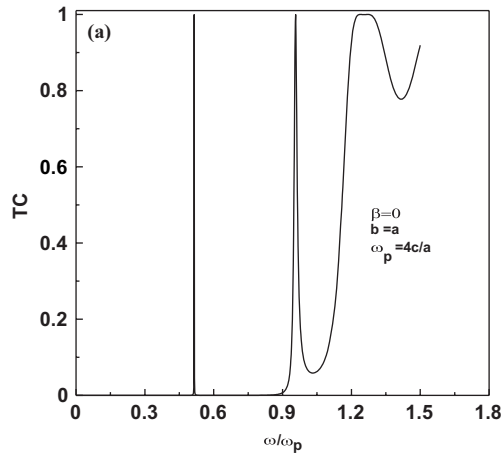


FIGURE 2.5

Projected PBS for a 1D PPC; shaded areas denote photonic bands. (Shiveshwari 2011a.)

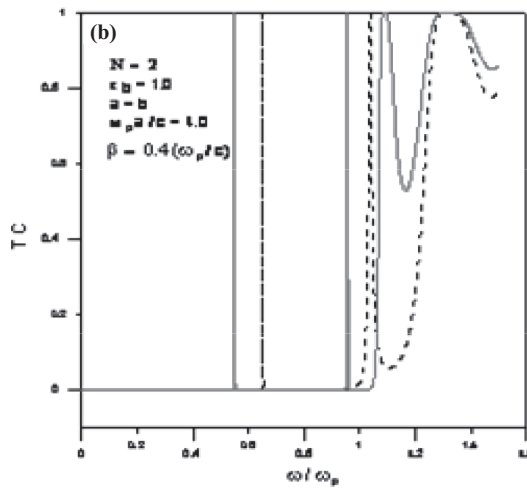
**FIGURE 2.6**

Projected PBS for a 1D PPC; shaded areas denote photonic bands. (Shiveshwari 2011a.)

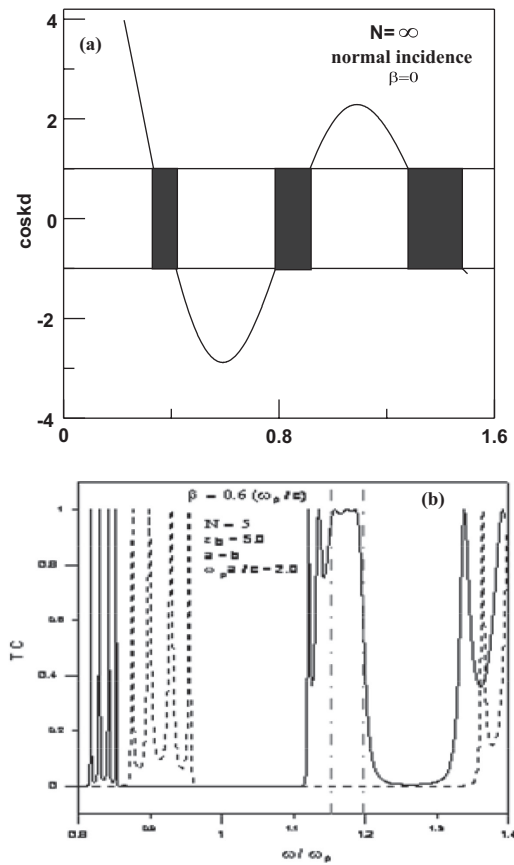
**FIGURE 2.7A**

TC versus frequency for (a) normal incidence. (Shiveshwari 2011b.)

Figure 2.7 suggests that it can transmit a mechanically suitable narrow band of frequency of light, which finds its application in spectrometers, monochromators, and optical filters with super narrow transmission band. Near $\omega = \omega_p$, a gap exists only for TM polarization (solid), whereas for TE (dashed) polarization, there will be complete transmission. We then study the PBS in Figure 2.8a for normal incidence and TC versus frequency for TE (dashed) and TM (solid) polarizations in Figure 2.8b for $a = b = 2c/\omega_p$, $\epsilon_b = 5.0$, $\beta = 0.6 \omega_p/c$. For the frequency region between two dot-dashed vertical lines, almost all of the TM-polarized

**FIGURE 2.7B**

TC versus frequency for (b) oblique incidence, TE (dashed) and TM (solid) polarizations. (Shiveshwari 2011a.)

**FIGURE 2.8**

Plot of (a) dispersion relation versus ω/ω_p for normal incidence (b) TC versus ω/ω_p for TE (dashed) and TM (solid) polarizations. (Shiveshwari 2011a.)

contributions will be transmitted, while almost all TE polarization contributions will be reflected. In this way, the efficient polarization splitting is achieved in this frequency region. We see that the existence of band or gap, near $\omega = \omega_p$ for TM polarization, depends on different structural and plasma parameters. The study (Guo 2009) of the dispersion relation of 1D plasma dielectric PC for normal ($\beta = 0$) and oblique ($\beta = 0.3 \omega_p/c$) incidence shows that there exists strong dispersion around the plasma frequency. In [Figures 2.5 and 2.6](#), the first low frequency gap is a complete gap with a cutoff frequency. The band characteristics have been obtained for $N \geq 4$ (Lee and Yao 2003) in 1D PC. Here, the most striking feature is the appearance of PBG characteristics even for $N = 2$ system.

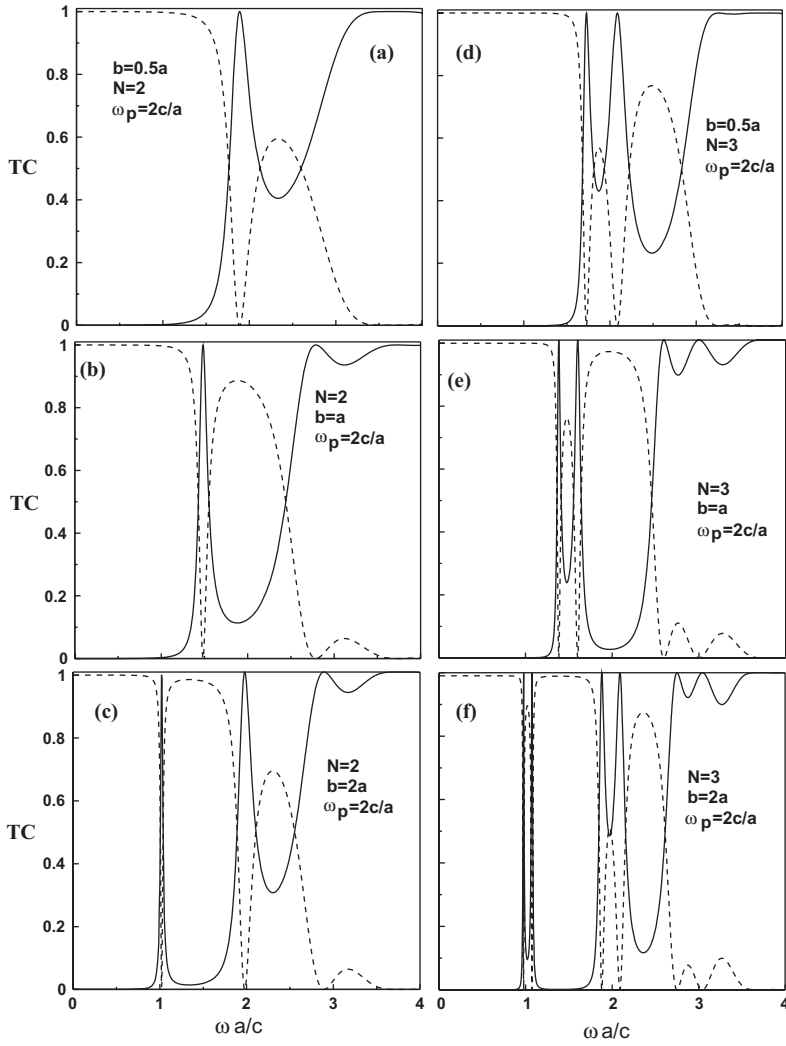
2.3.4 Variations of TC and PBG with Thickness of the Constituent Layers

The position and width of PBGs can be tuned by changing the thickness of the constituent layers in [Figures 2.9 to 2.11](#). [Figure 2.9](#) shows normal incidence and finite PC. [Figures 2.10 and 2.11](#) show oblique and infinite PC. Relations of TC (solid) and RC (dotted) with the frequency have been shown by keeping ω_p constant for $N = 2$ in [Figure 2.9a–c](#) and for $N = 3$ in [Figure 2.9d–f](#). The results clearly show that the gap regions shift toward the higher frequency for increase in plasma width (relative width compared with air). Such a shift has also been reported for metal dielectric PCs. However, there is no shift with change in the number of unit cells, and the position and widths of allowed and forbidden regions remain the same. [Figure 2.10](#) shows the PBG characteristics as a function of “ b ” while plasma width $a = 2c/\omega_p$ is kept constant. In [Figure 2.11](#), we show the gap characteristics as a function of “ a ” while the width of the dielectric materials $b = 2c/\omega_p$ is kept constant. The position of first allowed (and forbidden) band shifts toward the higher frequency with increase of plasma width.

2.3.5 Variations of TC and PBG with Dielectric Constant

[Figure 2.12](#) shows the band characteristics and TC versus frequency for $a = b = 2c/\omega_p$, $\varepsilon_b = 5.0$. We have taken $\varepsilon_b = 5.0$ in [Figures 2.8 and 2.12](#). It is clear that the phase velocity decreases leading to more gaps for the larger value of ε_b . The first and second gaps are complete gaps for both polarizations. There is a new band near $\omega = \omega_p$ for TM polarization, which is not present for TE polarization and normal incidence. Our study elucidates the projected PBS for $\beta = 0$ to $\beta = 0.6 \omega_p/c$ for both TE and TM polarizations showing the existence of (1) new band or gap near plasma frequency and (2) complete PBGs for both polarizations.

In the above discussion, absorption is not considered, which may affect the properties of 1D plasma dielectric PCs. However, it has been shown that increasing collision frequency (Deng and Liu 2009) has little effect on gap width. The incident angle effectively controls the gap width and gap location.

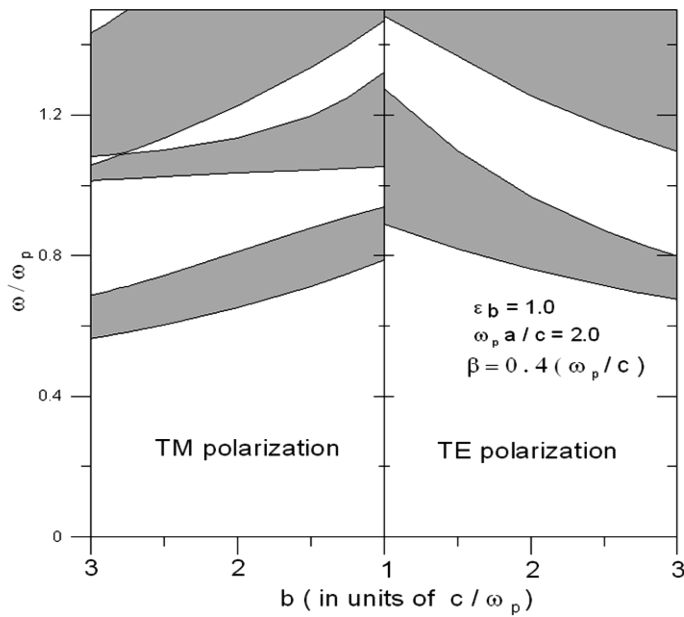
**FIGURE 2.9**

Plot TC and RC for (a) $b = 0.5a$, (b) $b = a$, (c) $b = 2a$ (for $N=2$) (d) $b = 0.5a$, (e) $b = a$, (f) $b = 2a$ (for $N=3$) versus $\omega a/c$ for wave propagation along the periodic axis for PPC. (From Shiveshwari, L. and Mahto, P., *Solid State Commun.*, 138, 160–164, 2006.)

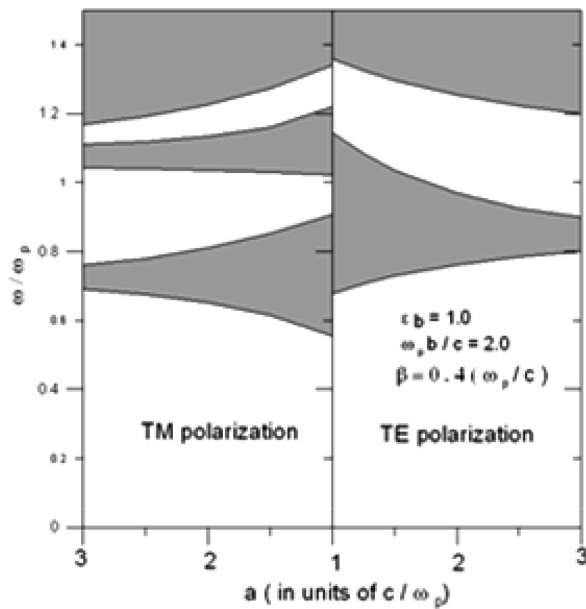
2.4 Conclusion

We have presented the theoretical analysis of band characteristics in 1D periodic structure and applied the boundary condition: continuity of field components. We have used the TMM, an elegant and systematic approach to solve 1D problem with economy of mathematical expressions, which has the advantage of yielding precise results and its versatility in studying a wide range of 1D periodic structure.

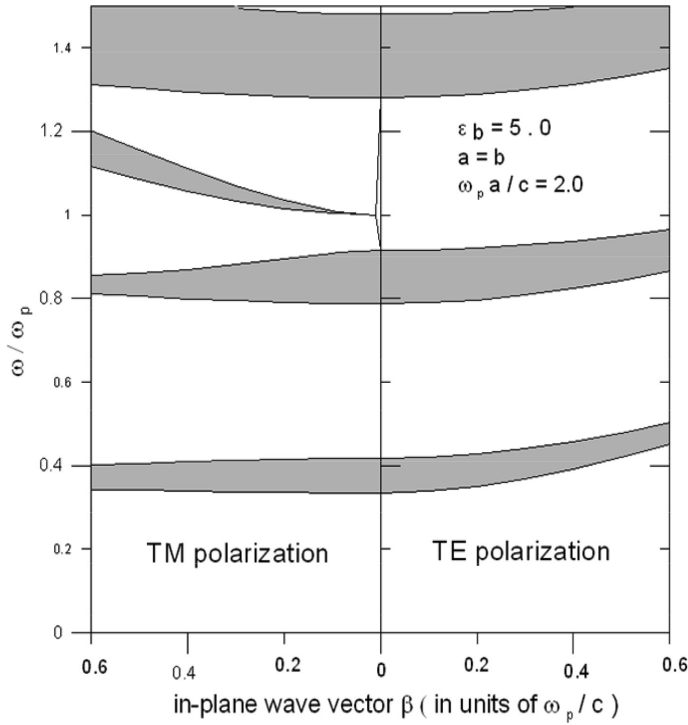
The generalized expression for TC through an N period structure is obtained using the time-reversal symmetry, which is valid for any 1D periodic structure. TC and band

**FIGURE 2.10**

PBS as a function of “ b ” while $a = 2c/\omega_p$ is kept constant; shaded regions denote photonic bands. (Shiveshwari 2011a.)

**FIGURE 2.11**

PBS as a function of “ a ” while $b = 2c/\omega_p$ is kept constant shaded regions denote photonic bands. (Shiveshwari 2011a.)

**FIGURE 2.12**

Projected PBS for a 1D PPC shaded areas denote photonic bands. (Shiveshwari 2011a.)

structure can be calculated only from T_1 and $\cos \phi$. Also, without having detailed information on the unit cell profile, we can have some information about T_N . Band structure, which is a characteristic of fully periodic system, is obtained through TC studies for finite systems. Bandgaps are obtained where the transmission rates drop to negligible values, which helps in the estimation of the system size needed to get the band characteristics. The dispersion relation for the 1D periodic dielectric structure exhibits K-P type behavior similar to the model for electrons. The infinite structures are very expensive and difficult to fabricate and work within laboratory. Our study shows the exact number of unit cells required to form the band structure. Even if the TC does not drop to zero, the relatively high and low values exhibit the precursor of band structure. The band structure and consequently the size of the gaps are very sensitive to the filling fraction of different materials in the superlattice structure. The frequencies (energies) relevant to resonant transmission lie in the allowed bands ($\text{Tr } M \leq 2$) of an infinite periodic structure and for which there cannot occur any resonant transmission lie in the forbidden regions ($\text{Tr } M > 2$) of the same periodic structure.

We have theoretically analyzed the transmission and RCs and PBG effect in 1D plasma dielectric PCs. The wave propagation through plasma–air PCs shows the existence of PBG characteristics even when N is very small and also for infinite plasma PCs. Study of Al_2O_3 –air PCs indicates that more unit cells are required to obtain deep transmission minima. Formation of band characteristics and dependence of bandgap on width and density of plasma layer are the clear indication of strong PBG effects due to global coupling between different unit cells in different layers. We discuss the dependence of TC and PBG on angle of

incidence, layer thickness, number of unit cells, and dielectric constant of the dielectric material. The numerical results show that the band width of the PBG increases with the increase of plasma density. We notice that even with a small number of unit cells, the present structure exhibits precursors of band characteristics with intervals of restively high or low transmission. The expression for TC allows us to explore the emergence of full band structure as N increases. The exact analysis for a finite number of unit cells becomes critical for understanding a complete process. The wave propagation through plasma dielectric PCs shows the existence of PBG characteristics even for $N = 2$ system and also for infinite plasma dielectric PCs. A striking feature is that they may allow a narrow range of frequency of light wave to propagate in plasma dielectric PCs and transmission becomes large, because of which a super narrow transmission band filtering device can be designed. Our results show that at least one low frequency complete PBG exists for both polarizations. The existence and shift of first forbidden gap extending to zero frequency can be explained by the combined effect of waveguide cutoff attenuation and a global PBG effect. We can regulate the plasma and structural parameters, such as plasma layer width, plasma density, dielectric layer width, permittivity of the dielectric medium, and number of unit cells, to achieve the regulation of plasma dielectric PC. We have shown that periodic multilayer containing plasma layer can exhibit a new type of band or gap near frequencies where the electric permittivity changes sign. For propagation along the stratification direction, these bands or gaps can be completely absent, whereas for oblique propagation, they emerge for TM polarization. This is due to the singular behavior of the dispersion relation for TM polarization. In contrast to Bragg PBGs originating from interference mechanism, this effect is produced by strong dispersive character of plasma material. We also showed how such a structure can function as a highly efficient polarization splitter. The interesting findings, such as existence of complete PBGs for both polarizations, band characteristics for few N systems, super narrow transmission band, gap, or band near $\omega = \omega_p$, could render possible novel applications of plasma dielectric PC in a wide wavelength range. If the plasma width is taken in a micrometer and millimeter range, the plasma PCs can provide important advantages to filters and other plasma functional devices in infrared and millimeter wave regime, the results of which can be used for developing potential applications in optoelectronic devices.

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3

Introduction to Photonic Crystal Fibers

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3.1 Introduction

One of the significant technological advances in the twenty-first century is the discovery of optical fibers, which came into existence with the revolution in the communication systems. Optical fibers can transmit information at a very high speed in the form of short optical pulses, which are widely used in optical sensors, soliton lasers, bio-photonics, spectroscopy, medicine, and so on besides optical communications. A conventional optical fiber usually relies on light being guided by the total internal reflection, which is achieved by introducing a core with a higher refractive index compared with the surrounding medium known as cladding. Despite the remarkable performance in many fields, the conventional optical fibers have several limitations such as endlessly single-mode operation, extremely large or small core area at the single-mode wavelength, anomalous group velocity dispersion at visible and near-infrared wavelengths, controllable dispersion, and large optical nonlinearity. A different category of fibers, called photonic crystal fibers (PCFs), were first proposed by Knight et al. (1996).

Unlike the conventional optical fibers, PCFs exhibit a large number of unique properties such as single-mode operation over a large band of wavelengths (Birks et al. 1997), unique-dispersion characteristics, very high birefringence (Chen et al. 2004), large-mode area (LMA) (Knight et al. 1998a), high numerical aperture (HNA) (Wadsworth et al. 2004), and very large or small optical nonlinearity (Sharma and Konar 2015; Sharma et al. 2015). These unique properties are applied in fiber optic devices and sensors (Broderick et al. 1999; Saitoh and Koshiba 2002; Peucheret et al. 2003; Saitoh and Koshiba 2004; Sang et al. 2005; Zhang and Demokan 2005; Dong et al. 2007; Liu et al. 2013; Ayyanar et al. 2017; Vigneswaran et al. 2018).

3.2 Photonic Crystal Fibers

In general, PCFs comprise a single material, usually undoped silica, with an array of air holes running along the length of the fiber. These air holes are arranged in a lattice pattern. One and more air holes are omitted from the central region of the cross-section of the fiber, which acts as the core, while the background material along with the low-index air holes that run parallel to the fiber axis form the effective cladding. The schematic of a PCF is shown in [Figure 3.1](#). The main difference between the two fibers is that PCF features an air–silica cross-section and made up of a single material, whereas a conventional optical fiber has an all-glass

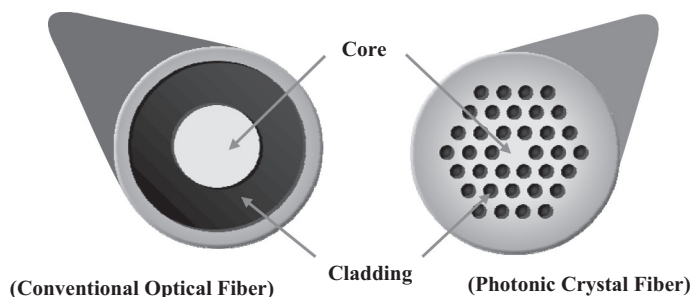


FIGURE 3.1

Schematic diagrams of the conventional optical fiber and photonic crystal fiber.

cross-section and made up of two or more materials. In a PCF, other advantages such as the arrangement of air holes, air-hole size, and hole-to-hole distance provide additional factors in the fiber design, which facilitate complete control over its optical properties. High-design flexibility is the most important characteristic of a PCF, which provides excellent optical properties such as high nonlinear coefficient, endless single mode operation, and high birefringence.

PCF is fabricated with large effective nonlinearity, which can be achieved by tight mode confinement and use of glasses with greater intrinsic material nonlinear coefficient than silica. The dispersion properties of the PCF can be tailored as desired due to high-design flexibility. For example, besides shifting the zero dispersion wavelength at the visible region, the dispersion can be made uniform over a wide range of wavelengths.

Introduction of significant asymmetry in the core region helps achieving high birefringence in PCFs, and PCFs with proper geometric characteristics are used to obtain endlessly single-mode operation. These unique optical properties have made them useful in many applications such as dispersion compensation, sensor design, development of optical nonlinearity-based devices, high power delivery, spectroscopy, and fabrication of supercontinuum lasers.

The first optical fiber was fabricated from a single low-loss material (fused silica) at Bell Laboratories by Kaiser and Astle (1974) in 1973. In 1987, Sajeew John from the University of Toronto and Eli Yablonovitch from Bell Communications Research, originally, predicted the concept of photonic bandgap (PBG) structure (John 1987). Thereafter, in 1995, Birk and coworkers proposed a hollow-core optical fiber that guides light using PBG (Birks et al. 1995). In 1996, they introduced the idea that light can be propagated through a hollow-core fiber (HCF), which is surrounded by air holes configured in a triangular lattice pattern. Later, these fibers were known as PCFs; as for optical mode propagation, they depend on the properties of photonic crystals. Significant achievements in PCFs have been shown in [Figure 3.2](#).

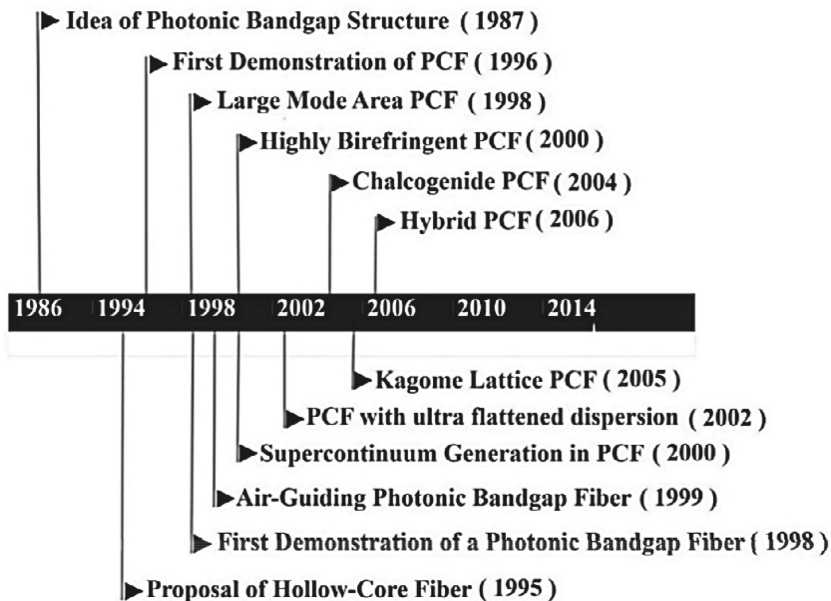


FIGURE 3.2

Important developments of photonic crystal fibers.

3.3 Classification of PCFs

PCFs are broadly classified into two main categories based on their guiding principles: (a) index-guiding fibers and (b) PBG-guiding fibers (Cregan et al. 1999), which are further divided into subcategories based on their structure and optical properties. Similar to the conventional optical fibers, in index-guiding PCFs, light guiding is a result of total internal reflection. In contrast, light is guided through a photonic bandgap in PBG-guiding fibers. The classification of PCFs has been shown in Figure 3.3. Index-guiding fibers are further subdivided into the following five categories: (i) highly nonlinear (HNL) fibers, which consist of very small core to hold tight confinement of the optical mode (Kaiser and Astle 1974; Broderick et al. 1999; Peucheret et al. 2003; Nasilowski et al. 2005; Sang et al. 2005; Méchin et al. 2012; Sharma and Konar 2015; Sharma et al. 2015); (ii) LMA fibers having relatively large core, which helps optical mode to spread out (Knight et al. 1998a; Mortensen et al. 2002; Limpert et al. 2003; Folkenberg et al. 2004; Nielsen et al. 2004); (iii) HNA fibers having very large core, which is surrounded by a low index material ring (Mortensen 2002;

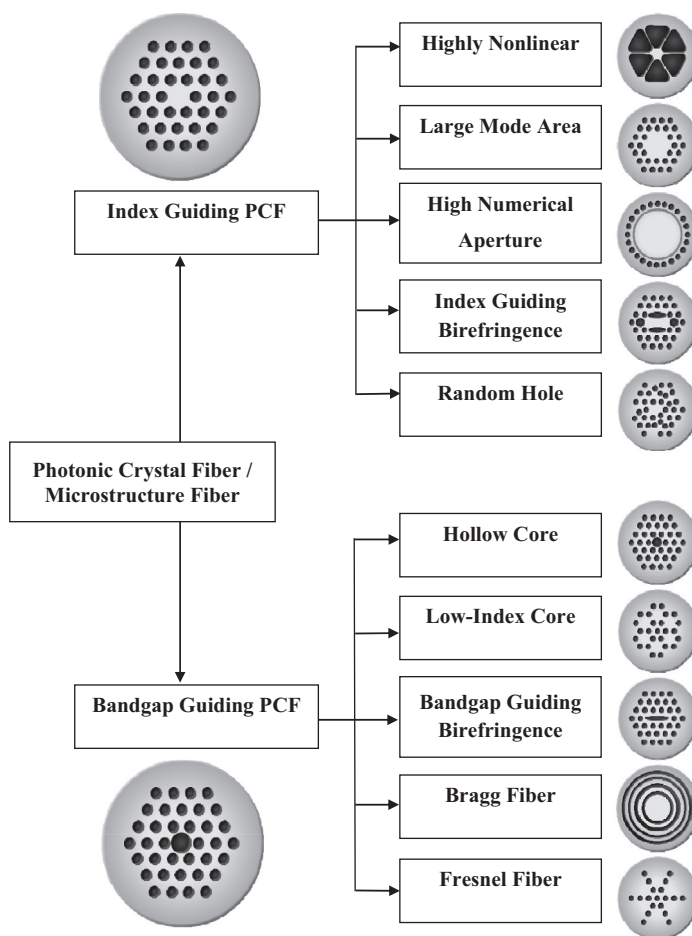


FIGURE 3.3

Classification of photonic crystal fibers.

Davidson and Bokor 2004; Wadsworth et al. 2004); (iv) index-guided highly birefringent fibers (IG HBFs), which contain an elliptical solid core region to maintain polarization of the propagating mode (Dong et al. 2007; Liu et al. 2013; Ayyanar et al. 2017; Vigneswaran et al. 2018); and (v) random air-hole fibers (RAHFs), which contain the random distribution of air holes in the cladding region. Similarly PBG-guiding fibers are divided into the following subcategories: (i) HCFs, where the light is guided through the hollow core, that is, air or vacuum (Birks et al. 1995; Cregan et al. 1999; Temelkuran et al. 2002; Xiao et al. 2007); (ii) low index fiber (LIF) in which light is guided through a low index core due to the bandgap effect; (iii) bandgap-guiding highly birefringence fibers (BG HBFs), which possesses elliptical hollow core to achieve high birefringence (Chen et al. 2004); (iv) Bragg fibers in which rings of high and low index materials are alternately arranged; and (v) Fresnel fibers, which contain air holes distributed in Fresnel's zone.

3.3.1 Index-Guiding PCFs

In general, a high-refractive index core region in this type is surrounded by a lower refractive index material, which act as the cladding. The refractive index of the cladding is lowered by creating a microstructure of air holes, which are arranged in a regular pattern that runs along the length of the fiber. As a reflecting core and cladding interface are not clearly defined, the guiding principle is not exactly the total internal reflection, but it is the modified total internal reflection from core and effective cladding (Xiao et al. 2007). In general, a typical cross-section of the fiber contains a triangular lattice of air holes, which is shown in Figure 3.4. The cladding structure may be altered by varying air-hole diameter d and hole-to-hole spacing (pitch) Λ , which define the structure geometry of the fiber.

The optical beam that is confined within the fiber core propagates as a guided mode with a propagation constant β along the fiber axis. The highest value of β that can exist in an infinite homogeneous medium with refractive index n is $\beta = nk_0$, where k_0 is the free-space propagation constant. In a PCF, the refractive index of the core is $n_{\text{core}} = n_{\text{silica}}$, and the effective refractive index of the cladding region is defined in terms of the propagation constant of the lowest order mode that can propagate in the finite cladding material that is, $n_{\text{eff}} = \beta/k_0$, where n_{eff} is the effective refractive index of the cladding.

3.3.2 Photonic Bandgap-Guiding PCFs

The idea of guiding light through PBG has originated from the fact that light propagation in a periodic arrangement of dielectrics can be suppressed at certain wavelengths. The bands of frequencies over which propagation is forbidden are known as PBG. In a PBG fiber, making an additional large hole at the center exposes the periodicity of the arrangement of air holes

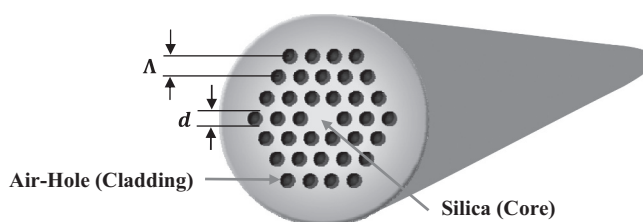
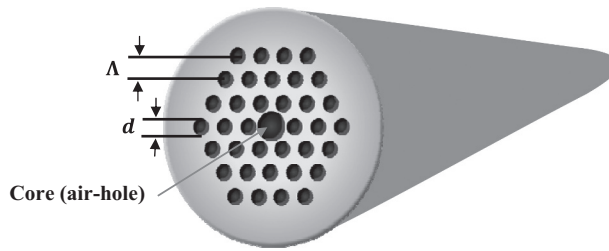


FIGURE 3.4

Cross-sectional view of an index-guiding PCF with a triangular lattice of air holes.

**FIGURE 3.5**

Cross-sectional view of a hollow-core PCF with a triangular lattice of air holes in the cladding region.

in the cross-section of the fiber. This extra hole is known as a defect in the photonic crystal structure and acts as a fiber core. The defect can support optical mode, which falls within the PBG of the surrounding photonic crystal. Thus, optical modes falling within the PBG will be strongly confined to the defect. The cross-sectional view of a hollow-core PBG fiber with a triangular lattice of air holes is shown in [Figure 3.5](#) (Cregan et al. 1999; Xiao et al. 2007).

3.4 Optical Properties

Desired, unique, and optical properties of a PCF can be achieved by creating an appropriate air-hole pattern and changing hole diameter (d), hole pitch (Λ), and a number of air-hole rings and by appropriately choosing these design parameters. Due to the large varieties of arrangement of air holes, PCFs provide a wide possibility to control the refractive index contrast between the core and the photonic crystal cladding. Therefore, PCFs that exhibit single modeness over a wide range of wavelengths (Birks et al. 1997), uniform dispersion (Saitoh and Koshiba 2004; Zhang and Demokan 2005), high as well as low non-linearity (Broderick et al. 1999; Peucheret et al. 2003; Saitoh and Koshiba 2004; Sang et al. 2005; Sharma and Konar 2015; Sharma et al. 2015), and large birefringence can be tailored (Ortigosa-Blanch et al. 2000; Hansen et al. 2001; Ju et al. 2003; Knight 2003; Chen and Yu 2006; Yue et al. 2007; Li et al. 2008a; Ademgil and Haxha 2009; Konar et al. 2009; Hu et al. 2013; Sharma et al. 2013). Hence, PCFs exhibit new and improved optical properties that are not achievable in conventional optic fibers.

3.4.1 Dispersion

Dispersion is a process in which various frequency components of an electromagnetic wave are separated due to the variation of refractive index with frequency. When an optical pulse propagates through a medium that exhibits frequency-dependent refractive index, various frequency components of the pulse travel at different velocities through the medium and are separated resulting in the spreading of the pulse in a temporal domain. The phenomenon is known as a group velocity dispersion (GVD), and no new frequency component is generated in this process. Two types of dispersive medium are normal and anomalous. The former shows a higher frequency components that travel at a slower speed compared with the lower frequency components, whereas the latter shows the exact opposite. Dispersion plays a vital role in the transmission of optical

pulses through optical fibers (Gander et al. 1999; Knight et al. 2000). Although GVD is the primary dispersion mechanism, other dispersion mechanisms, such as waveguide dispersion, polarization mode dispersion, and intramodal dispersion, also contribute to the total dispersion in the fiber.

In a single-mode PCF and in a conventional single-mode fiber, the total dispersion is due to two different sources. The first one is the material dispersion, which arises due to the frequency dependence of the refractive index n . The second factor that contributes to the dispersion is the waveguide dispersion, which originates from the way in which the spatial distribution of the optical mode changes with the wavelength. The waveguide dispersion depends on the refractive index contrast between the core and the effective cladding in a PCF. PCFs provide new possibilities of dispersion control with respect to their tailorable waveguide dispersion.

The value of total dispersion in a single-mode PCF is the sum of material dispersion $D_M(\lambda)$ and waveguide dispersion $D_W(\lambda)$, that is, $D_C(\lambda) = D_M(\lambda) + D_W(\lambda)$. The waveguide dispersion $D_W(\lambda)$ of the PCF can be directly calculated using the following relation:

$D_W(\lambda) = -\lambda/c d^2 n_{\text{eff}} / d\lambda^2$, where c is the velocity of light in vacuum, λ is the wavelength, and n_{eff} is the modal effective index ($n_{\text{eff}} = \lambda/2\pi\beta$), and β is the propagation constant. Material dispersion $D_M(\lambda)$ of a particular material depends on its refractive index, which can be calculated using Sellmeier's equation (Malitson 1965) $n^2(\lambda) = 1 + \sum_i B_i \lambda^2 / (\lambda^2 - C_i)$, where B_i and C_i are Sellmeier's coefficients of the material. For bulk fused silica, $B_1 = 0.6961663$, $B_2 = 0.4079426$, $B_3 = 0.8974794$, $C_1 = 0.0684043 \mu\text{m}$, $C_2 = 0.1162414 \mu\text{m}$, and $C_3 = 9.896161 \mu\text{m}$ (Sharma and Konar 2015), and for SF57 glass, $B_1 = 1.8165127$, $B_2 = 0.42889364$, $B_3 = 1.07186278$, $C_1 = 0.0143704198 \mu\text{m}$, $C_2 = 0.0592801172 \mu\text{m}$, and $C_3 = 121.419942 \mu\text{m}$ (Sharma et al. 2015).

3.4.2 Birefringence

Fiber birefringence is an important optical property, which has been widely used in coherent optical communications and in the fabrication of fiber optic sensors (Gloge 1974; Rao et al. 2003). The electric field of a propagating electromagnetic wave is always aligned in a particular direction, called polarization. When a linearly polarized light enters the fiber core with anisotropic refractive index distribution, the entering light splits into two different mutually orthogonal polarized modes. These two orthogonal modes propagate with two different velocities that depend on the refractive index of the fiber along the direction of polarization. The difference of refractive indices along two mutually perpendicular directions is known as the birefringence.

In optical fibers, birefringence results from small variations in the cylindrical symmetry of the fiber core and asymmetrical stress distribution. As this birefringence changes randomly along the length of the fiber, it limits data transmission rate in long-distance high-bit rate systems. Large birefringence suppresses the effect of random variation of birefringence.

3.4.3 Loss Mechanism

Loss is an important property of optical fibers. After extensive investigations, the loss in conventional optical fibers has been reduced from a very large to a very low value. Conventional fused silica fibers exhibit loss less than 0.2 dB/km at telecommunication wavelength of 1550 nm (Kaiser and Astle 1974), whereas PCFs show loss of 0.28 dB/km at the same wavelength (Chen and Shen 2007). There are different types of loss mechanisms, which have been discussed later.

3.4.3.1 Intrinsic Loss

The air-hole surface roughness results in intrinsic loss. During the fabrication process, scratches and contamination affect air-hole surfaces. If the surface roughness of air hole is comparable with wavelength, then it can significantly increase the scattering loss, which can be reduced by improving the etching and polishing process.

3.4.3.2 Confinement Loss

The leakage of the optical mode from the fiber core results in confinement loss. The air holes in the cladding region are arranged in such a way that the refractive index contrast is adequately maintained, so that the optical field remains in the core region. Inadequate refractive index contrast causes light to move away from core to the cladding region, thereby increasing confinement loss. Hence designing the effective cladding with appropriate value of air-hole pitch and air-hole diameter will help reducing the confinement loss, which can be even reduced to negligible levels by proper design of the cladding structure.

3.4.3.3 Bending Loss

In conventional fibers, the bending loss arises when a fiber is bent more than a certain critical radius. If the wavelength of light is longer than a certain value, the fiber loses its guiding property. PCFs show identical behavior and are more sensitive to bending loss due to the complex cladding structure, and accurate modeling of this loss in PCF is a challenging task. Increase in air-hole spacing and its diameters reduces the bending loss.

3.4.4 Nonlinearity

Conventional optical fibers exhibit a very small optical nonlinearity of $\sim 1 \text{ W}^{-1}\text{km}^{-1}$. The optical nonlinearity is inversely proportional to the effective mode area. The manufacturing process allows for the fabrication of fibers with a very small core diameter ($\sim 1-2 \mu\text{m}$) and a high air-filling fraction. Consequently, the propagating mode shows a very small mode area compared with the conventional fibers (Broderick et al. 1999; Peucheret et al. 2003; Saitoh and Koshiba 2004; Sang et al. 2005; Zhang and Demokan 2005; Sharma and Konar 2015; Sharma et al. 2015). Therefore, in a PCF, large effective nonlinearity can be achieved by tight mode confinement and use of glasses with greater intrinsic material nonlinear coefficient than silica. The effective nonlinear coefficient (γ) of the fiber can be calculated using $\gamma = (2\pi n_2 / \lambda A_{\text{eff}}) \times 10^3 \text{ W}^{-1}\text{km}^{-1}$ (Brechet et al. 2000; White et al. 2001; Bjarklev et al. 2003), where $A_{\text{eff}} = (\int_{-\infty}^{\infty} |E|^2 dx dy)^2 / \int_{-\infty}^{\infty} |E|^4 dx dy$, E is the electric field of the propagating optical mode, and A_{eff} is the effective area of the optical mode. For bulk fused silica, the value of nonlinear index $n_2 = 2.16 \times 10^{-20} \text{ m}^2/\text{W}$, and for lead silicate (SF57), $n_2 = 4.1 \times 10^{-19} \text{ m}^2/\text{W}$ (Sharma and Konar 2015; Sharma et al. 2015). The proper fiber design and the choice of appropriate material can produce very large optical nonlinearity in PCFs.

3.4.5 Effective V-Parameter

In a conventional fiber, V-parameter determines the single modeness of the fiber. For $V \leq 2.4$, conventional fibers follow single-mode operation, and they become multimode for $V \geq 2.4$. Similarly in PCFs, the single modeness is ensured by an effective V-parameter, which

is defined as (Kaiser and Astle 1974; Birks et al. 1997). $V_{\text{eff}} = 2\pi \frac{\Lambda}{\lambda} \sqrt{n_o^2 - n_{\text{eff}}^2}$, where n_o is the core refractive index and n_{eff} is the effective refractive index of cladding. The value of $V_{\text{eff}} \leq 4.1$ ensures single-mode operation in PCFs.

3.5 Fabrication Processes

The fabrication of a PCF plays a main role in achieving the desired optical properties, which is complicated compared with the conventional fiber due to the complex cladding structure. Different techniques are used to fabricate PCFs depending on their cladding structure and materials.

3.5.1 Stack and Draw Technique

Birk et al. introduced stack and draw process for the fabrication of PCFs (Razzak and Namihira 2008), which became popular among the scientific community due to its simplicity. This fabrication process starts with the creation of a preform, which contains the air-hole structure on a microscopic scale. The preform is created by stacking a number of capillary silica tubes and rods to form a desired air-silica structure. This process provides flexibility in designs that can be maintained throughout the fiber length. The capillaries of silica tubes and rods are bound together with a thin wire and fused together after the stacking process. The fused preform structure is pulled down in a conventional fiber drawing tower. In a conventional optical fiber, the temperature is maintained around 2100°C, whereas in a PCF, usually a lower temperature of ~1900°C is maintained. The pressure and temperature are very important parameters and are accurately controlled during fiber drawing. Finally, the PCFs are coated with a standard jacket, which provides strength to the fiber. Using this method, hollow-core PCFs could also be drawn by removing some elements from the fiber stack.

3.5.2 Extrusion Process

Compound glasses are not available in the form of tube. Making preform of compound glasses through extrusion is easier due to low softening temperature. The molten glass is forced through a die containing an appropriate design pattern of holes in the extrusion process, during which fibers are drawn directly from the bulk glass using a fiber drawing machine. PCFs of chalcogenide glasses and polymers are also made using this process.

3.5.3 Drilling Technique

Drilling process is used for the fabrication of a polymer material-based PCFs, which may be helpful in fabricating PCFs with arbitrary cladding structure. This method is extremely time consuming for the fabrication of complex structures and usually associated with a large contamination in the preform. These contaminants ultimately increase the propagation loss in the fiber. This method is suitable for the fabrication of short-length fiber.

3.5.4 Rolling Technique

The cigar-rolling technique can be used to fabricate PCFs of polymer–glass combination (Temelkuran et al. 2002). In this technique, multilayer mirrors are rolled to form a preform with a hollow core, which uses two material configurations in such a way that the fiber maintains radial variation in the refractive index. The radial index variation has intrinsic advantages to form hollow-core fibers, which are surrounded by a solid multilayer structure to increase the refractive index contrast, which leads to large PBGs and omnidirectional reflectivity.

3.6 Applications of Various PCFs

PCFs have various applications in optical communications, signal processing, spectroscopy, gas sensing, and fiber-based devices. They are designed to achieve the desired optical properties, which are suitable for specific application. In brief, application of some specific fibers are described later.

3.6.1 Large-Mode Area Fibers

It is possible to fabricate fibers with LMA by appropriately designing the cladding structure. Such LMA fibers are obtained by creating low refractive index contrast between the core and the cladding. These LMA fibers are currently used in UV and visible wavelengths. They are used to deliver high-power optical beams for welding and machining. These fibers can transport large power without damage (Broeng et al. 1999; Larsen et al. 2003; Kristiansen et al. 2005), which provide significant advantages over conventional optical fibers.

3.6.2 Highly Nonlinear PCFs

Optical nonlinearity can be exploited to fabricate useful fiber optic devices. PCFs can be designed with high refractive index contrast between the core and the cladding by making large air holes or by reducing the core dimension. This configuration helps strong confinement of the guided mode that leads to enhancement of nonlinear coefficient. Some applications require PCFs with high nonlinear coefficient and specific dispersion profile. Fibers with high nonlinear coefficient and zero dispersion at communication wavelength (1550 nm) are useful in many important applications such as multiple clock recovery, 2R regeneration, pulse compression, parametric amplifiers, wavelength conversion, all optical switching, and supercontinuum-based sources for wavelength division multiplexing (WDM). (Broderick et al. 1999; Peucheret et al. 2003; Saitoh and Koshiba 2004; Sang et al. 2005; Zhang and Demokan 2005).

3.6.3 High Numerical Aperture PCFs

These are multimode fibers having low bend loss. These fibers can collect light from broad angle and emit light into broad angle at the output end and have a wide range of applications such as endoscopy, high-power source, wind mill warning signal, and optical sensors (Mortensen et al. 2002; Davidson and Bokor 2004; Saitoh and Koshiba 2004; Wadsworth et al. 2004).

3.6.4 High Birefringence

In some applications, such as sensing and maintenance of optical polarization, one needs a fiber with large birefringence. PCFs exhibit birefringence that could be 10–100 orders larger than the conventional optical fibers. The introduction of large asymmetry in the fiber structure can yield large birefringence (Saitoh and Koshiba 2002; Dong et al. 2007; Liu et al. 2013; Ayyanar et al. 2017; Vigneswaran et al. 2018).

3.6.5 Dispersion Compensation

Dispersion is a key parameter of an optical fiber. A conventional optical fiber is restricted to a particular dispersion value, whereas in PCF, the dispersion properties can be controlled by introducing appropriate cladding structure. Significant improvements have been made to use optical fibers as dispersion compensating elements in optical communication systems. The dispersion compensating scheme is based on the use of fibers with large negative (normal) dispersion to balance the dispersion of standard optical fibers at the communication wavelength of 1550 nm. Due to design flexibility, large normal dispersion can be easily obtained in PCFs in the communication bandwidth. Hence, PCFs have been contemplated for use in dispersion compensation as they exhibit large normal dispersion over optical communication wavelengths (Engeness et al. 2003; Poli et al. 2003; Yin et al. 2006; Thyagarajan and Pal 2007).

3.6.6 Applications of Bandgap-Guiding PCFs

Bandgap-guiding PCFs have their own importance due to low nonlinear coefficient and high damage threshold. These fibers are suitable for investigation of nonlinear optical processes in gases that require high intensities at low power, long interaction length, and good quality transverse beam profile. These fibers have several other important applications, such as high-power continuous wave (CW) beam delivery, machining and welding, laser-Doppler velocimetry, and laser surgery (Broeng et al. 1999; Mussot et al. 2007; Xiao et al. 2007; Bhattacharya et al. 2009).

3.7 PCF Modeling

Due to complex structure, investigation of optical properties of PCFs analytically is not worth pursuing. Hence, optical properties of PCFs are generally investigated adopting a suitable numerical technique. After Knight and colleagues in 1996 demonstrated the first experiment, a number of modeling techniques have been used to characterize PCFs, which are plane-wave expansion method (Ferrando et al. 2000; Johnson and Joannopoulos 2001), localized-function method (Mogilevtsev et al. 1999; Monro et al. 2000), approximate effective index model (Knight et al. 1998b; Søndergaard et al. 1998; Li et al. 2008b), finite element method (Brecht et al. 2000), multipole method (White et al. 2001; Kuhlmeier et al. 2002), finite difference frequency domain (FDFD) method (Zhu and Brown 2002), and finite difference time domain (FDTD) method (Taflöv and Hagness 2000; Qiu 2001; Vu et al. 2008). A detailed comparison of these methods has been made by Gallagher and Design (2008). The principle characteristics of these methods are summarized in [Table 3.1](#), and merits and demerits are listed in [Table 3.2](#).

TABLE 3.1

Characteristics of the Various Methods Used for PCF Modeling

Methods	Modal Properties	Modal Accuracy	Limitations	Computational Efforts
Effective Index	MFD, β	Inaccurate at longer λ	Polarization analysis impossible	Low
Localized Function Expansion	MFD, β , A_{eff}	Accurate	Relatively complex	High
Plane-Wave Expansion	MFD, β , A_{eff}	Fair	Infinite cladding assumption	Intensive
Multipole Expansion	MFD, β , A_{eff}	Accurate	Symmetric structures	Intensive
Finite Difference Time Domain	MFD, β , A_{eff} , Propagation	Reliable	Sums overall excited modes	Very intensive
Finite Difference Frequency Domain	MFD, β , A_{eff} , Propagation	Reliable	Sums overall excited modes	High
Beam Propagation	MFD, β , A_{eff} , Propagation	Reliable	Inefficient	High

Source: Bjarklev, A. et al., *Photonic Crystal Fibers*, Kluwer Academy Publishers, London, UK, 2003.

Note: MFD: mode-field diameter, β : propagation constant, A_{eff} : effective area, λ : wavelength.

TABLE 3.2

Overview of Advantages and Disadvantages Concerning Different Numerical Methods Used for Analysis and Design of PCFs

Method	Advantages	Disadvantages
Effective Index Method	Simple Low computation time	No polarization property Inaccurate modal property No PBG analysis possible
Localized Function Method	Solution may be adapted to finite size structures Describe random hole distribution	Needs great care on result interpretation Real complex method Inefficient PBG analysis
Plane-Wave Method	Well suited for PBGs Good agreement with experiments demonstrated Widespread approach	Large supercell needed for complex structures Very demanding for full fiber analysis
Multipole Method	Describe effects of finite cladding region No false birefringence errors Suited for symmetry studies Leakage loss prediction	Cannot analyze arbitrary cladding configurations
Finite Difference Time Domain Method	Very general approach Describe arbitrary structures Well established and tested	Nonmodal approach Numerically intensive Required detailed treatment of boundaries
Finite Difference Frequency Domain Method	Describe arbitrary structures. Well established and tested.	Nonmodal approach Numerically intensive Required detailed treatment of boundaries
Beam Propagation Method	Reliable method Commercially available Use complex property constant	Computationally inefficient

Source: Bjarklev, A. et al., *Photonic Crystal Fibers*, Kluwer Academy Publishers, London, UK, 2003.

3.7.1 FDTD Method

FDTD technique has been used to analyze the optical properties of PCFs (Taflöv and Hagness 2000; Qiu 2001; Saitoh and Koshiba 2002; Saitoh and Koshiba 2004; Gallagher and Design 2008; Vu et al. 2008; Konar et al. 2009; Bhattacharya and Konar 2012a; Sharma et al. 2013; Sharma and Konar 2015; Sharma et al. 2015; BandSOLVE). The FDTD method is applied to describe the arbitrary structure and user friendly, and a wide range of wavelength response may be achieved in a single simulation. FDTD is a time-domain process, which calculates the H and E electromagnetic fields at each point of computational domain and provides real-time graphical representation of electromagnetic field propagation in the fiber. In a conventional three-dimensional (3D) FDTD method (Taflöv and Hagness 2000; Qiu 2001; Vu et al. 2008), Yee's algorithm (Gallagher and Design 2008) has been implemented to discrete Maxwell's equation for electric and magnetic fields in a Cartesian coordinate. Basically, there are three steps to solve a 3D arbitrary structure by FDTD method. First, each E component is surrounded by four H components, and each H component is surrounded by four E components. Second, the leapfrog time-step adopted, where all the E components in the 3D spaces are calculated and stored in memory for a particular time point using the H data previously stored in memory. Then all the H data are calculated and stored in memory using the E data just computed. And then finally, all derivatives in Maxwell's equations, including the space derivatives and time derivatives, are replaced by the central finite difference. The FDTD method allows to specify the materials at all points within the gridded computational domain and also allows to choose a wide variety of linear and nonlinear dielectric and magnetic materials, which can be easily modeled. As FDTD requires that the entire computational domain be gridded, and the grid spatial discretization must be sufficiently fine to resolve both the smallest electromagnetic wavelength and the smallest geometrical feature in the model, very large computational domains can be developed, which results in very long solution times.

3.8 Review and Future Scope

Since their discovery in 1996, PCFs have garnered the attention of research and industrial communities, where they are used in different applications, such as optical communications, fiber optic sensors, gas sensing, optical signal processing, and optical nonlinearity-based devices, due to their novel characteristics. In particular, PCFs with high birefringence are desirable for sensing and optical communication-based applications, which rely on the maintenance of state of polarization of optical field. Designing PCFs with enhanced effective optical nonlinearity and controlled dispersion helps contribute to the development of supercontinuum sources at low power.

In conventional optical fibers, birefringence is achieved either by introducing stress in the fiber profile or by creating asymmetry in the core region. However, in conventional optical fibers, achievable birefringence is small due to a small index contrast (Gloge 1974). In contrast, the large index contrast between the core and the cladding helps in achieving high birefringence. Several authors have investigated birefringence of the index-guiding PCFs in which the birefringence is introduced either by asymmetric core design, by change of a few air holes (Ortigosa-Blanch et al. 2000; Hansen et al. 2001), or by squeezed crystal

lattice, which means that the air-hole diameter along two orthogonal axes is different (Zhang and Yang 2004). Some polarization maintaining fibers use elliptical air holes to produce high birefringence (Steel and Osgood 2001a, 2001b; Konar et al. 2009). Saitoh and Koshiba (2002) have studied birefringence in a bandgap-guiding PCF with asymmetric air core. Experimental results of high birefringence ($\sim 10^{-3}$) at a wavelength of $1.55 \mu\text{m}$ in bandgap-guiding PCFs have been reported (Chen et al. 2004). Wang et al. (2006) have proposed bandgap-guiding PCFs with elliptical air holes. Recently, Lyngsø et al. (2010) have reported two different types of polarizations maintaining solid PCFs that guide light by a combination of a PBG and total internal reflection. They have studied group and phase birefringence experimentally and numerically, whose value of the order of $\sim 10^{-4}$. Recently, Sharma et al. (2013) have reported highly birefringent $\sim 2.2 \times 10^{-2}$ in an index-guiding PCFs with a low walk-off value. Bhattacharya and Konar (2012b) have investigated a new type of bandgap-guiding PCF, which promises to yield birefringence $\sim 5.22 \times 10^{-2}$.

Supercontinuum (SC) generation is the most important application among the diverse applications of PCFs. The interest in SC generation is triggered by several important applications such as optical coherence tomography (Aguirre et al. 2006), optical metrology (Udem et al. 2002), spectroscopy (Saitoh and Koshiba 2004), frequency comb generation (Husakou and Herrmann 2003), and WDM (Kawanishi et al. 1999). PCFs hold strong optical mode field inside the fiber core, which leads to large effective nonlinearity. Due to large effective optical nonlinearity, the threshold power requirement for the SC generation in a PCF is low; thereby it becomes an attractive medium for generating wideband SC.

In 1970, Alfano and Shapiro first reported the measurements of frequency broadening in glasses and crystals using Nd:Glass mode-locked laser (Stone and Knight 2008).

Ranka et al. (2000) were the first to demonstrate SC generation in a PCF. They demonstrated broadening of SC spectra from 400 to 1450 nm by pumping 100 fs pulses of 800 pJ energy at 790 nm in a 75 cm long PCF that exhibits zero dispersion at 767 nm. Thereafter, a significant number of research works have been carried out to understand the underlying mechanisms behind the broadband SC generation (Ranka et al. 2000; Frosz et al. 2005; Dudley et al. 2006; Gorbach and Skryab 2007; Price et al. 2007; Kudlinski and Mussot 2008; Barviau et al. 2009; Xiong et al. 2009; Begum et al. 2010; Heidt 2010; Boucon et al. 2011; Hartung et al. 2011; Tiwari and Janyani 2011; Gattass et al. 2012; Price et al. 2012; Xing-Ping et al. 2013). Considerable efforts have been made to study SC in PCFs with a single zero dispersion wavelength (Begum et al. 2010). Several authors have directed their efforts to achieve enhanced frequency shifting in the shorter wavelength regime (Gorbach and Skryabin 2007; Sharma et al. 2015), which is possible only when appropriate group index matching is satisfied (Kudlinski and Mussot 2008; Stone and Knight 2008). Enhanced SC bandwidth with improved flatness has been demonstrated using PCFs with two zero dispersion wavelengths (Frosz et al. 2005; Barviau et al. 2009). Moreover, recently, it has been shown that multiwavelength pumping provides significant enhancement of the SC bandwidth (Xiong et al. 2009; Hartung et al. 2011). Due to large optical nonlinearity, non-silica fibers have been exploited to generate SC in the wavelength range of $2\text{--}5 \mu\text{m}$ (Price et al. 2007; Boucon et al. 2011; Tiwari and Janyani 2011; Gattass et al. 2012). Solid-core PBG fibers have also been investigated to generate SC in the visible region (Sharma and Konar 2016). SC generation due to slow nonlinear response in a liquid-filled PCF and modulation instability-induced SC due to saturated nonlinear response have also been examined (Gorbach et al. 2006; Pureur and Dudley 2011).

Although tremendous advancements have been made in understanding physical mechanism and in the use of these fibers in real-life applications, many issues need to be resolved

in order to fully exploit the potential of these fibers. For example, bandgap-guiding and index-guiding PCFs exhibit birefringence of $\sim 5.22 \times 10^{-2}$ and $\sim 2.22 \times 10^{-2}$, respectively. Furthermore, the large value of birefringence can be improved by tuning in structure and material. It is now well understood that low uniform dispersion and large nonlinearity are key to broadband efficient SC generation. Unfortunately, in index-guiding PCFs, large optical nonlinearity is associated with large dispersion as well, which is detrimental to efficient SC generation. Hence, a trade-off between dispersion and nonlinearity is needed to achieve the optimal result.

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4

Nonlinear Optics and Supercontinuum Generation in Photonic Crystal Fibers

Mohit Sharma and S. Konar

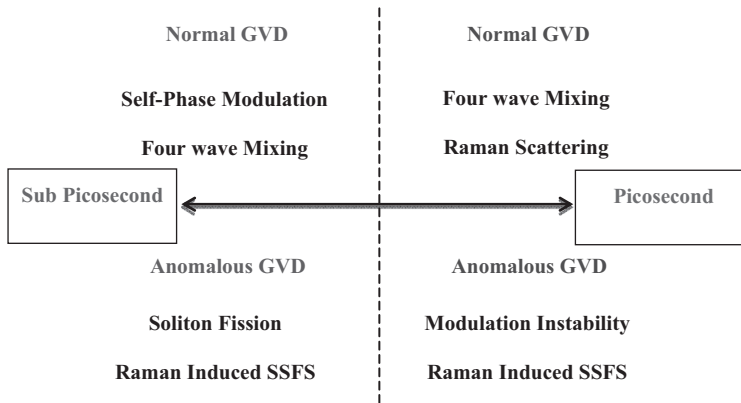
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4.1 Introduction

Supercontinuum (SC) generation is the significant spectral broadening of a pump pulse due to a host of nonlinear effects. Many nonlinear phenomena simultaneously take place to produce spectrally continuous output, which include self-phase modulation (SPM), cross-phase modulation (XPM), Raman scattering, modulation instability (MI), four wave mixing (FWM), soliton fission, and soliton self-frequency shift (SSFS). Moreover, dispersive waves also contribute to the SC generation. The role of these nonlinear phenomena is controlled by the combination of pulse duration, pumping wavelength, fiber dispersion, and nonlinearity, altering which results in significant changes in the shape, spectral width, and coherence properties of the SC.

The SC spectra are usually generated by pumping femtosecond or picosecond pulses in a highly nonlinear photonic crystal fiber (PCF) with an anomalous group velocity dispersion (GVD) regime of the fiber that is close to the zero dispersion wavelength (ZDW). In this case, spectral broadening is contributed by a host of nonlinear phenomena such as SPM, MI, and stimulated Raman scattering (SRS), in addition to the third- and higher-order dispersions. This process can produce a broad SC spectrum; however, the SC generation mechanism is extremely sensitive to pump pulse fluctuations. Small fluctuation in the pump amplitude or phase from shot to shot causes significant fluctuations in the spectral intensity and phase of the resulting SC, leading to the loss of spectral coherence.

**FIGURE 4.1**

Summary of dominant mechanism for SC generation in different pulse and dispersion regimes. (From Alexander, V.V. et al., 2012. *Opt. Fiber Technol.* 18, 349–374, 2012.)

If the pump wavelength is shorter than the ZDW, that is, in the normal dispersion region of the fiber, then pump pulses cannot form solitons. The spectral broadening is influenced by SPM, XPM, Raman scattering, and FWM under this pumping regime, which is less efficient and is narrower compared with that produced when the pumping is in anomalous dispersion regime. This is due to the rapid temporal spreading of the pulse under SPM and normal dispersion. Nevertheless, there is an advantage in generating SC in the normal dispersion regime. The spectral broadening is not seeded from noise and does not amplify pump fluctuation. Thus pumping in the normal dispersion regime improves the coherence and spectral flatness. We have summarized the spectral broadening mechanism due to pumping in the normal and anomalous dispersion regimes in [Figure 4.1](#). In the next few sections, we have given brief descriptions of important nonlinear phenomena, which are responsible for SC generation.

4.2 Four Wave Mixing

FWM is a process in a nonlinear medium involving two pump waves with frequencies ω_1 and ω_2 and a Stokes and an anti-Stokes waves with frequencies ω_S and ω_{AS} , respectively (Stolen and Bjorkholm 1982; Stolen et al. 1989). Each wave passing through the nonlinear medium sets up a modulation of the refractive index of the medium. When two waves of frequencies ω_1 and ω_2 pass through the medium, the modulation in the refractive index of the medium will have new terms with the new frequency components given by $\omega_S = 2\omega_1 - \omega_2$ and $\omega_{AS} = 2\omega_2 - \omega_1$, which is known as nondegenerate FWM. Light at new frequencies is generated, provided that there is sufficient phase matching, that is, the phases of the generated waves must be matched in order for the effective accumulation of newly generated frequencies to take place. The effective phase mismatch between waves is given by the following:

$$\Delta k = \beta(\omega_{AS}) + \beta(\omega_S) - \beta(\omega_1) - \beta(\omega_2) + 2\gamma P_0, \quad (4.1)$$

where $\beta(\omega_i)$ is the propagation constant at frequency ω_i , and the last term accounts for the nonlinear phase shift due to the intensity-dependent refractive index. In most cases, it is assumed that $\omega_1 = \omega_2 = \omega_p$, and for such cases, Δk can be expanded around the common frequency ω_p as

$$\Delta k = 2 \sum_{n=1}^{\infty} \frac{\beta_{2n}(\omega_p)}{(2n)!} \Omega_s^{2n} + 2\gamma P_0, \quad (4.2)$$

where $\Omega_s = \omega_p - \omega_s = \omega_{AS} - \omega_p$. The parameter β_{2n} is the $2n$ th derivative of $\beta(\omega)$. This special case (i.e., $\omega_1 = \omega_2 = \omega_p$) is known as degenerate FWM. The significant FWM occurs only if the phase mismatch nearly vanishes. The FWM is the underlying mechanism of many nonlinear effects including SPM, cross-phase modulation, and MI.

4.3 Self-phase Modulation

A propagating optical pulse in a nonlinear medium experiences a phase modulation due to the self-induced change in the nonlinear refractive index, which is known as the SPM. In the simplest case, the nonlinear refractive index (n) of the medium is due to the Kerr nonlinearity, which can be described as follows:

$$n = n_0 + n_2 |E(z, t)|^2, \quad (4.3)$$

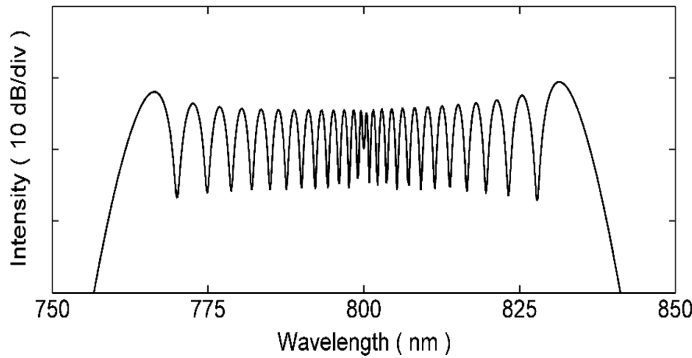
where n_0 is the linear refractive index, z is the direction of propagation, and n_2 is the nonlinear index coefficient. The nonlinear phase shift $\phi_{nl}(z, t)$ due to the intensity-dependent change in the refractive index is given by the following:

$$\phi_{nl}(z, t) = n_2 \frac{\omega}{c} z |E(z, t)|^2. \quad (4.4)$$

The nonlinear phase shift is time dependent as the intensity profile of the pulse is time dependent. It translates into optical spectral broadening (Silva et al. 2012) due to nonlinear temporal dependence of the chirp $\delta\omega(t) = -\frac{\partial\phi_{nl}(z, t)}{\partial t}$, thus generating new frequencies as the pulse propagates inside the medium. Temporal shape of the pulse remains unaffected.

Through SPM, ultrashort pulses with a high peak power lead to substantial spectral broadening of hundreds of nanometer wavelengths. Typically, strong oscillations appear in the spectrum of the pulse. For example, the structure of a typical spectral broadening of a short pulse due to SPM effect alone has been shown in [Figure 4.2](#).

SPM is extensively investigated in highly nonlinear PCFs. SPM in optical fibers has many important applications. In principle, the PCFs are used to compress or broaden an optical pulse by using the SPM effect. The compression of optical pulses as short as 4 fs using SPM in PCFs has been reported (Emaury et al. 2014). Furthermore, the spectral broadening of more than two octaves of optical pulses due to SPM has also been reported (Benjamin and Feir 1967; Hasegawa and Brinkman 1980; Zakharov and Ostrovsky 2009; Silva et al. 2012; Hudson et al. 2014; Jiang et al. 2015; Liang et al. 2015).

**FIGURE 4.2**

SPM induced spectral broadening of a typical short pulse at 800 nm.

4.4 Modulation Instability

In a nonlinear medium, the fluctuations on the envelope of continue wave (CW) or quasi-continuous waves can develop, leading to the distribution of energy from the central wave frequencies to neighboring frequencies. In the time domain, this is characterized by the splitting of the wave into series of ultrashort pulses and in the spectral domain generation of frequency side bands. This process is termed as MI or in some other systems known as Benjamin–Feir instability (Benjamin and Feir 1967; Zakharov and Ostrovsky 2009). The main requirement is anomalous dispersion. When a perturbation causes a small increase in the intensity at one temporal position, this part of the field undergoes SPM and then compression due to the anomalous dispersion. The peak intensity thus increases, and the process continues to happen. The requirement of physical parameters for such instabilities to occur is the same as those of soliton propagation. Thus, MI is known as a precursor to optical solitons (Karpman 1967; Hasegawa and Brinkman 1980; Tai et al. 1986). The frequency shift at the maximum MI gain (Hasegawa and Brinkman 1980) is given by the following:

$$\Delta\omega_{MI} = \sqrt{\frac{2\gamma P_0}{|\beta_2|}}, \quad (4.5)$$

and the maximum sideband gain $g_{max} = 2\gamma P_0$, where P_0 is the pump power. The MI period is then simply $T_{MI} = 2\pi/(\Delta\omega_{MI})$. This period is critical for determining the SC dynamics.

4.5 Self-steepening

The phenomenon arises due to the intensity dependence of the group index. In a nonlinear medium, the peak of a propagating pulse experiences higher group index than the rest of the pulse and therefore propagates with a lower velocity than the rest of the pulse. Consequently, the intensity gradient of the leading edge is reduced, and the intensity

gradient of the trailing edge is enhanced. The spectral broadening through SPM becomes asymmetric when self-steepening is significant. To conserve energy in the FWM process (Agrawal 2007), the broadening on the short wavelength side of the spectrum is more while the spectral intensity is higher in the longer wavelength side. Self-steepening is more significant for short pulses.

4.6 Raman Scattering

Raman scattering is an inelastic process in which energy is transferred to or from a material due to molecular vibrational or rotational motion. A Stokes photon with energy $\hbar\omega_S$ is scattered when the vibrational state of a molecule is excited by a photon of energy, $\hbar\omega_P$ ($\omega_P > \omega_S$). An anti-Stokes photon of energy, $\hbar\omega_{AS}$ ($\omega_{AS} > \omega_P$), can also be created under appropriate condition although likelihood of this process is low. Due to the amorphous nature of the material, the molecular vibrational states of silica glass form a continuum; hence, Raman scattering can occur over a broad range of frequency shifts. Raman scattering can occur spontaneously; however, this process is a relatively weak effect. SRS is a nonlinear inelastic process in which highly efficient scattering can occur under the influence of high-intensity laser beam. SRS can occur within solitons whose bandwidth exceeds the Raman gain bandwidth in silica. The low-frequency components of solitons/optical pulses experience amplification at the expense of the high frequencies, and the overall effect is that the pulse shifts to the longer wavelengths, which is known as SSFS (Lee et al. 2008).

SSFS is experimentally and theoretically investigated by several researchers. A highly nonlinear PCFs can offer SSFS in a very short length. Liu et al. (2001) demonstrated SSFS of 200 fs pulses from 1300 to 1650 nm wavelength with greater than 60% efficiency in a 15-cm long tapered PCF. Washburn et al. (2004) also demonstrated SSFS in the wavelength region of 850–1050 nm by pumping 100 fs pulses at 806 nm in 1.7 m long PCF. Nishizawa et al. (2001) have generated wavelength-tunable femtosecond soliton pulse at 780–900 nm using ultrashort pulse fiber laser at 780 nm in a 60 cm long highly nonlinear PCF. Petropoulos et al. (2003) have observed 80 cm SSFS at telecommunication wavelengths in a 2.2 m long lead silicate PCF with ~ 2 ps pulses with average power of 110 mW at a repetition rate of 1.25 GHz.

4.7 Dispersive Waves

Dispersive waves are linear waves that can propagate in any dispersive medium. However, their amplitudes remain negligible until an appropriate phase-matching condition is satisfied. These waves can be generated inside a fiber as a byproduct of nonlinear process within the fiber. For example, when a soliton undergoes non-adiabatic transformation, a stable soliton state may emerge after the shedding of excess energy as dispersive radiation. Dispersive waves located at certain phase-matched frequencies and overlapping with the soliton spectrum receive a transfer of energy from the soliton. The phenomenon can be understood as a tunneling effect from self-trapping solitons to free propagating radiation and is analogous to the Cherenkov radiation (Karpman 1993; Akhmediev and Karlsson 1995; Husakou and Herrmann 2001; Skryabin and Yulin 2005; Silva et al. 2012). This clearly requires that the

soliton to be relatively broadband (short duration) and to be propagating close to ZDW. These dispersive waves can grow at the cost of radiation emitted by the perturbed soliton when they propagate with the same phase velocity as that of solitons (Hartl et al. 2001). If ω_{dw} and ω_s are frequencies of the dispersive waves and of the soliton, respectively, then at a distance z after a delay of $T = z/v_g$, the two phases are, respectively, given by the following:

$$\phi_{dw} = \beta(\omega_{dw})z - \omega_{dw}(z/v_g), \quad (4.6)$$

$$\text{and } \phi(\omega_s) = \beta(\omega_s)z - \omega_s(z/v_g) + \frac{1}{2}\gamma P_0 z, \quad (4.7)$$

where v_g is the group velocity of the soliton. The last term represents the nonlinear phase shift occurring only for the solitons and P_0 is the peak power of solitons. To achieve phase matching, the following condition should be satisfied:

$$\beta(\omega_{dw}) = \beta(\omega_s) + (\omega_{dw} - \omega_s)/v_g + \frac{1}{2}\gamma P_0. \quad (4.8)$$

Solutions of the above equation determine the frequency ω_{dw} of one or more dispersive waves generated because of soliton perturbation. If we expand $\beta(\omega_{dw})$ in Taylor series around ω_s , then the above equation can be rewritten as

$$\sum_{n \geq 2} \frac{\beta_n(\omega_s)}{n!} \Omega_d^n - \frac{1}{2}\gamma P_0 = 0, \quad (4.9)$$

where $\Omega_d = \omega_{dw} - \omega_s$. As β_2 must be negative for soliton propagation, the phase matching condition cannot be met without any higher-order dispersion term. In the above equation, if we keep terms up to third-order dispersion, then the above equation reduces to

$$\Omega_d \cong -\frac{2\beta_2}{\beta_3} + \frac{\gamma P_0 \beta_3}{3\beta_2^2}. \quad (4.10)$$

When $\beta_3 > 0$, the phase matching is possible only at higher frequencies (as $\beta_2 < 0$). This is the conventional situation where dispersive waves of wavelengths in the normal dispersion region at shorter wavelengths than the zero dispersion are excited and are most important in terms of SC generation. Another possibility is for $\beta_3 < 0$, and the dispersive waves to be at lower frequencies than the soliton. This case is found when a red-shifting soliton meets a second zero dispersion wavelength at the long wavelength edge of the SC (Biancalana et al. 2004).

4.8 Soliton Fission

Soliton fission leads to the generation of broadband spectrum, wherein pulse breaking develops mainly due to the higher-order effects or soliton dynamics. Either higher-order dispersion terms or Raman scattering can cause perturbation to the constituent

fundamental solitons of the pump pulse, leading them to move with the differing group velocities, and hence break apart or fission. A higher-order soliton of order N will emit N fundamental solitons, which are emitted in the decreasing order of peak intensity. They can undergo SSFS, forming a continuum of solitons Raman shifted to different wavelengths and due to dispersion, different temporal positions if a soliton is propagating close to ZDW, then some energy can be transferred into normal dispersion regime. Consequently, a broadband SC is generated. For this process to dominate, the MI must not occur. MI will occur if the MI period is sufficiently smaller than the pump pulse duration.

4.9 Modeling of “Supercontinuum” Generation

To obtain optical SC, high-power input pulses, known as pump pulses, are launched near the zero dispersion point in a highly nonlinear PCF. The propagation dynamics of these pulses through the PCF can be described by the well-known generalized nonlinear Schrödinger equation (GNLSE) (Silva et al. 2012; Jiang et al. 2015), which is given as follows:

$$\frac{\partial}{\partial z} A(z, \tau) = -\frac{\alpha}{2} A(z, \tau) + \sum_{n \geq 2} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial \tau^n} A(z, \tau) + i\gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial \tau} \right) A(z, \tau) \int_{-\infty}^{\infty} R(\tau') |A(z, \tau - \tau')|^2 dT', \quad (4.11)$$

where $A(z, t)$ is the envelope of the electric field of the input pulse, α is the fiber loss, $\beta_n = d^n \beta / d\omega^n$ is the n th order dispersion at the pumping wavelength λ_p , and ω_0 is the central angular frequency of the pump pulse. R is the Raman response function, which consists of an instantaneous electric response and a contribution from delayed Raman response, which may be defined as follows:

$$R(\tau) = (1 - f_r) \delta(\tau) + f_r h_r(\tau),$$

$$\text{where } h_r(\tau) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2^2} \exp\left(\frac{-\tau}{\tau_2}\right) \sin\left(\frac{\tau}{\tau_1}\right).$$

The value of f_r , τ_1 , and τ_2 is material dependent. For lead silicate PCFs, $f_r = 0.1$, $\tau_1 = 5.5$ fs, and $\tau_2 = 32$ fs (Kalashnikov et al. 2007). In contrast, for silica PCFs, $f_r = 0.18$, $\tau_1 = 12.5$ fs, and $\tau_2 = 32$ fs (Frosz et al. 2005; Dudley et al. 2006). To examine the SC generation mechanism, we need to solve the GNLSE. The numerical solution of this equation by split-step Fourier method (SSFM) (Agrawal 2007) has been discussed in the next section.

4.9.1 Split-Step Fourier Method

SSFM was first used to investigate optical pulse propagation in optical fibers in 1973 (Yunakovsky 2006). Thereafter, a large number of investigations have been reported

till date (Hudson et al. 2014). A brief and elegant description of the SSFM has been outlined by Agrawal in *Nonlinear Fiber Optics* (Zakharov and Ostrovsky 2009). The right-hand side of Equation (4.11) can be splitted into a linear operator $\hat{D}$ and a nonlinear operator $\hat{N}$ and then it can be expressed as follows:

$$\frac{\partial A}{\partial z} = [\hat{D} + \hat{N}]A, \quad (4.12)$$

where $\hat{D}$ is a linear differential operator that accounts for dispersion and absorption and $\hat{N}$ is a nonlinear operator that governs all nonlinear interactions associated with the propagating pulse in the fiber. These operators are defined as follows:

$$\hat{D} = \sum_{n \geq 2} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial \tau^n} A(z, \tau) - \frac{\alpha}{2}, \quad (4.13)$$

and

$$\hat{N} = i\gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial \tau} \right) A(z, \tau) \int_{-\infty}^{\infty} R(\tau') |A(z, \tau - \tau')|^2 d\tau'. \quad (4.14)$$

When an optical pulse is propagating through the fiber, the dispersion and nonlinearity act together along the length of the fiber. SSFM obtains an approximate solution by pretending that over a small distance h , the dispersive and nonlinear effects act in the propagating pulse independently. More specifically, propagation from z to $z + h$ is carried out in two steps. In the first step, the nonlinearity N acts alone, and at that time, the value of D is assumed to be zero in Equation (4.12). In the second step, dispersion acts alone and N is set zero in Equation (4.12). Therefore, the propagating pulse after a step size h (Silva et al. 2012) becomes the following:

$$A(z + h, \tau) \approx \exp(h\hat{D}) \exp(h\hat{N}) A(z, \tau). \quad (4.15)$$

The exponential function $\exp(h\hat{D})$ can be evaluated in the Fourier domain as follows:

$$\exp(h\hat{D}) A(z, \tau) = F_T^{-1} \exp(h\hat{D}(-i\omega)) F_T A(z, \tau), \quad (4.16)$$

where F_T denotes Fourier transform operation and $\hat{D}(-i\omega)$ is obtained from Equation (4.13) by replacing $\frac{\partial}{\partial \tau}$ by $-i\omega$ and ω is the frequency in Fourier domain. The accuracy in SSFM is second order in step size h . The accuracy of the SSFM can be improved by adopting a slightly different procedure. In this scheme, instead of Equation (4.15), the solution of the pulse when it is propagating from z to $z + h$ is taken as follows:

$$A(z+h, \tau) \approx \exp\left(\frac{h}{2}\hat{D}\right) \exp\left(\int_z^{z+h} \hat{N}(z') dz'\right) \exp\left(\frac{h}{2}\hat{D}\right) A(z, \tau). \quad (4.17)$$

The main difference from the previous scheme is that the nonlinearity is included in the middle of the segment rather than at the boundary. Due to the symmetric form of exponential operators in Equation (4.17), the scheme is known as a symmetric-split-step-Fourier method (S-SSFM). The accuracy of this method is third order in the step size h . The step size h is small; thus the nonlinear contribution $\exp\left(\int_z^{z+h} \hat{N}(z') dz'\right)$ can be approximated as $\exp(h\hat{N})$ in Equation (4.17). However, the accuracy of the method can be further improved by evaluating the integral in Equation (4.17) more accurately than approximating it by $\exp(h\hat{N})$. Generally, the trapezoidal rule is used to evaluate the integral as follows:

$$\int_z^{z+h} \hat{N}(z') dz' \approx \frac{h}{2} [\hat{N}(z) + \hat{N}(z+h)]. \quad (4.18)$$

Unfortunately, $\hat{N}(z+h)$ is not known at the midsegment located at $z+h/2$, and hence evaluating Equation (4.18) is not simple. Therefore, it is necessary to follow an iterative procedure, which is initiated by replacing $\hat{N}(z+h)$ by $\hat{N}(z)$. Equation (4.17) is then used to estimate $A(z+h, T)$, which in turn is used to calculate the new value of $\hat{N}(z+h)$.

Although iteration process is time consuming, due to the improved accuracy in the numerical algorithm, the overall computation time can be reduced by increasing the step size h .

The implementation of the symmetrized SSFM is fairly straight forward. As shown in Figure 4.3, the fiber is divided into a large number of segments. The length of these segments need not to be same. The optical field $A(z, \tau)$ first propagates a distance $h/2$ with dispersion only, which can be calculated using the Fast Fourier Transform (FFT) algorithm given in Equation (2.16). At the midplane $z+h/2$, the field is multiplied by a nonlinear term

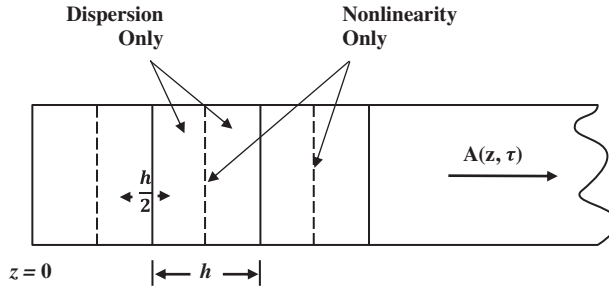


FIGURE 4.3

Illustration of the symmetrized split-step Fourier method used for numerical simulations. Fiber length is divided into large number of segments of width h . Within a segment, the effect of nonlinearity is included at the midplane shown by a dashed line.

that represents the effect of nonlinearity over the whole segment length h . Finally, the field is propagated through the remaining distance $h/2$ with dispersion only to obtain $A(z+h, \tau)$. In effect, the nonlinearity is assumed to be lumped at the midplane of each segment, which is shown by the dashed lines in [Figure 4.3](#).

4.10 Key Points for “Supercontinuum” Generation

The efficiency of the SC generation is controlled by pulse duration, pumping wavelength, fiber dispersion, optical nonlinearity of the fiber, and fiber attenuation (Ranka et al. 2000; Dudley et al. 2006; Frosz et al. 2005; Gorbach et al. 2006; Gorbach and Skryabin 2007; Price et al. 2007; Kudlinski and Mussot 2008; Stone et al. 2008; Barviau et al. 2009; Xiong et al. 2009; Begum et al. 2010; Heidt 2010; Raja et al. 2010; Boucon et al. 2011; Pureur and Dudley 2011; Hartung et al. 2011; Tiwari and Janyani 2011; Gattass et al. 2012; Price et al. 2012; Xing-Ping et al. 2013; Sharma et al. 2015; Sharma and Konar 2016). Due to large effective nonlinearity and controllable low uniform dispersion, PCFs have emerged as the most popular media for the efficient SC generation. The following issues should be given importance for the efficient SC generation:

1. Ultrashort pulses are desirable for the efficient generation of SC. Longer pulses require high peak power to activate nonlinear effects during pulse propagation.
2. The length of the PCF will be longer than the soliton fission length.
3. The effective optical mode area A_{eff} should be as small as possible in order to achieve large effective nonlinear coefficient γ . The value of A_{eff} affects the dispersion profile of the fiber. In general, lower A_{eff} increases the value of dispersion. Hence, the trade-off between nonlinearity and dispersion is very important in SC generation.
4. The wavelength of the pump pulses should be very close to the zero dispersion wavelength of the fiber.
5. In order to increase the nonlinearity of the medium, the core of the PCF may consist of a material with high nonlinear refractive index n_2 .
6. Besides pumping in the anomalous GVD regime, the SC can also be generated using pump pulses in the normal dispersion regime of the fiber. Pumping in the normal dispersion regime improves the coherence and spectral flatness. However, as a number of available nonlinear effects that are responsible for the SC broadening mechanism is limited, the broadening is narrower compared with the SC generated due to pumping in the anomalous dispersion regime.

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Effects of Various Parameters on Band Structure of Extrinsic Magnetized Cold Plasma Photonic Crystal

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5.1 Introduction

The two pioneering works of Yablonovitch (1987) and John (1987) laid the groundwork for the field of photonic crystal (PC), which has achieved a phenomenal growth during the last two decades. PCs are periodically structured electromagnetic (EM) media, usually a periodic optical nanostructure, in which there is periodic variation of dielectric constant with refractive indices of high contrast ratio and so prohibit propagation of certain frequency ranges, known as photonic bandgaps (PBGs) in analogy with electronic bandgaps as electron through periodic potential of semiconductors organize into electronic bands of various energies separated by electronic bandgaps. The coherence effect of scattering and interference results in PBGs, which occur in the scattering phenomenon for light traveling in the composite of periodic structure. Generally, these PCs are composed of dielectric, semiconductor, or metal surrounded by air with a periodically varying refractive index or electric permittivity having the lattice constant of the order of the wavelength

of light. Some of these crystals exist naturally, and nowadays, these are artificially engineered periodic structures with a high index contrast. Based on the periodicity, PCs are one dimensional (1D), two dimensional (2D), and three dimensional (3D) structures. Despite rectangular periodic structures, PCs are in the form of slabs containing two types: a square lattice of dielectric rods in air and a lattice of air holes in dielectric, which are referred to as the rod and hole slabs, respectively, and are examples of 2D PCs. Moreover, 3D PCs are composed of the following forms: a drilled dielectric (Yablonovite), a diamond lattice of air holes, an inverse opal, and a stack of alternating 2D crystals of rods or holes (Joannopoulos et al. 1995).

If a properly designed defect is introduced in a PBG structure, a strong localization of photon waves in the region near the defect takes place. The spectral gap found in such PCs leads to a variety of potential applications in designing different optical devices, and thus PCs are applicable in many areas such as optical filters, switches, waveguides, cavities, and design of more efficient lasers, hence achieved spectacular growth (Joannopoulos et al. 1995; Kumar and Rostami 2012).

A one-dimensional photonic crystal (1D PC), a periodic multilayer structure, is the most popular model and can easily be fabricated using the thin-film technology, which shapes and controls the light flow in optical technology in particular ways that use outside the range of conventional optics. 1D PCs play a huge role in various fields of optical engineering such as photonic device, optical filter, resonance cavity, laser application, high-reflecting omnidirectional mirror, and optoelectronic circuit (Fink et al. 1998; Chigrin et al. 1999; Krauss and Rue 1999; Gu et al. 2004; Sakoda 2004; Massaoudi et al. 2006; Busch et al. 2007; Zheng et al. 2007; Gaponenko 2010; Kumar et al. 2013). Such PCs can provide very high speed of operation, tolerance of temperature fluctuation, increased life time, and capability to care high repetition rates, compared with the conventional electronic devices.

5.1.1 Plasma Photonic Crystal

Moreover, plasma photonic crystal (PPC) has attracted a significant interest of researchers due to their tunable characteristics and advantages unlike conventional PCs composed of dielectrics or metals. The applied voltage, gas pressure, and temperature play a vital role in regulating plasma, so they enable us to realize the tunable photonic devices. Many researchers have investigated the optical properties of single-layer materials to understand the optics behind it. A one-dimensional plasma photonic crystal (1D PPC), with one of the periodic layers made of thin plasma, has made a remarkable attraction, which can be externally controlled and shows the features of both conventional PCs and plasma. The effects of plasma density, layer thickness, and dielectric constant on the dispersion characteristics of a binary 1D PPC were previously discussed by the researchers (Hojo et al. 2003; Hojo and Mase 2004). They determined the dispersion relation by solving a Maxwell wave equation using a method in analogy to Kronig–Penney’s problem, and they obtained the frequency gap and cutoff using the dispersion relation. Also, the dispersion relation of binary 1D PPC has already been discussed by Bin (2009) in obliquely incident EM waves, in which collision effect in plasma has been considered. Such PPCs are called intrinsic PPCs. Thus in 1D PPCs, there are two materials with distinct refractive indices, which are used like dielectric and plasma in periodic structures. Furthermore, some authors suggested tuning of photonic bands by varying different parameters such as plasma density, effective collision frequency, layer thickness, and the external magnetic field (Booker 1984; Hitoshi and Atushi 2004; Kumar 2012).

Some authors reported the use of magnetized cold plasma as a 1D extrinsic PPC, which provides gyro-effective frequency in presence of external magnetic field inside

the magnetized cold plasma. There are positive and negative values of the gyro-effective frequency, respectively, for the two types of polarizations, right-hand polarization (RHP) and left-hand polarization (LHP). Therefore, the magnetized cold plasma provides refractive index having specific characteristics due to the magnetic field variation, the effective collision frequency, and the electron density.

5.1.2 Extrinsic Plasma Photonic Crystal

In recent years, a new PPC called extrinsic plasma photonic crystal (EPPC) has been introduced, which is not periodic in nature but becomes periodic only in the presence of external magnetic field, which influences and leads to the creation of unit cells by periodic changes of plasma permittivity. EPPC bandgaps are externally controlled by applying a periodic magnetic field, where the altered magnitude of the magnetic field affects the bandgaps. Qi and Zhang (2011) reported the impact of various parameters, such as angle of incidence, magnetic field strength, and number of unit cells, on bandgap and reflection properties of magnetized cold plasma under a periodically varying magnetic field. Furthermore, King et al. (2015) discussed the band structure in a 1D PPC using magnetized cold plasma in bulk with a square wave-like magnetic field. Magnetized cold plasma plays a promising role in fabricating PC and tailoring optical properties of the periodic structure using its novel characteristics and thus can replace dielectrics and metals (Hitoshi and Atushi 2004; Qi and Zhang 2011; Kumar 2012; King et al. 2015). Kong et al. (2010) have proposed a narrow tunable filter with defect mode of the transverse electric (TE) wave from 1D PC doped with magnetized cold plasma.

More recently, Aghajamali et al. (2016) introduced the transmission property of 1D magnetized cold plasma-superconductor periodic multilayer structure for the applications in high-pass filters and reflectors. Thereafter, Dehnavi et al. (2017) have theoretically investigated the omnidirectional bandgap (OBG) in a tunable full PPC using the bulk cold plasma embedded in the DC periodic magnetic field and have shown the dependence of OBG on magnetic field, plasma density, and unit cell thickness. Kumar et al. (2018a) have reported an innovative idea to design tunable broadband reflector and narrowband filter using a dielectric and magnetized cold PPC.

5.1.3 A Chapter Overview

This chapter introduces EPPC, with cold plasma under a periodically varying magnetic field, and gives a detailed account of the band structure characteristics of a magnetized cold PPC, which is based on some recent literatures (Suthar and Kumar 2018; Kumar et al. 2018b). The idea of King et al. (2015) is extended here for oblique incident angles, and the effect of angle of incidence on the band structure of a 1D EPPC is explained. Here, the dependence of the band structure and the reflection spectra at oblique incident angles are only studied for transverse magnetic (TM) mode as TE mode at oblique incidence is less affected in such an extrinsic magnetized cold PPC (see Qi and Zhang 2011). The effects of other various parameters such as strength of applied magnetic field, electron density, and layer thickness ratio on band structure of 1D EPPC are explained for normal incidence. Using the transfer matrix method, the band structure and reflectance spectra are plotted against frequency in gigahertz (GHz), for the induced periodic structure of magnetized cold plasma in RHPs and LHPs, and are also discussed by varying the above-mentioned parameters. These parameters act as controlling factors for the bandgaps and are responsible for the blue and red shifts of the band edges. Such tunable band structure characteristics of the EPPC may be used in designing the optical filter and resonance cavity in photonic devices.

5.2 Theoretical Framework

5.2.1 Physical Model of 1D EPPC

It is well known that if bulk cold plasma is influenced by a periodic magnetic field, there exists an induced periodicity of refractive index along its length and acts as an EPPC. Figure 5.1 shows a 1D extrinsic magnetized cold PPC structure, $\text{air}/(AB)^N/\text{air}$, generated by applying an external periodic magnetic field $B(x)$, on bulk plasma in x - z plane having length L (Qi and Zhang 2011; King et al. 2015; Kumar et al. 2018b), which is given as follows:

$$B(x) = \begin{cases} -B & 0 \leq x \leq d_1 \\ +B & d_1 \leq x \leq d \end{cases} \quad (5.1)$$

Thus, PPC is generated by splitting bulk plasma into periodic layers of thicknesses d_1 and d_2 , respectively, where the number N of periods or unit cells is taken such that $L = Nd$ is satisfied with the spatial period $d = d_1 + d_2$. For the plasma material, the TE polarization (electric field perpendicular to xz plane) in EM wave will not be much affected by magnetic field $B(x)$ (Qi and Zhang 2011), and hence in the case of oblique incidences, the characteristics of TM polarization (magnetic field perpendicular to xz plane) are analyzed, whereas in the case of normal incidence, there will not be splitting of EM wave in TE and TM modes.

Here, 1D EPPC is in the form of $(AB)^N$, where A and B show the alternate layers of magnetized PPC. The dielectric constant of cold plasma $\varepsilon(\omega) = \text{Re}(\varepsilon) - i \text{Im}(\varepsilon)$ is given by King et al. (2015). The complex permittivity of magnetized cold plasma in forms of PPC layers can be given by the following:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 \left[1 - i \frac{\gamma}{\omega} \mp \frac{\omega_{le}}{\omega} \right]} \quad (5.2)$$

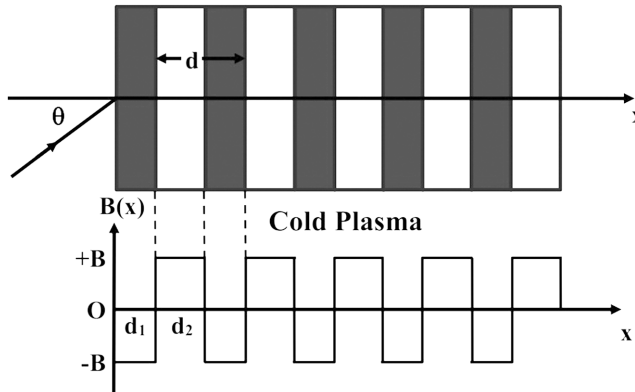


FIGURE 5.1

Extrinsic magnetized cold plasma photonic crystal structure with bulk cold plasma under a periodic magnetic field along x -direction.

In such an EPPC, the alternate induced layers are formed with the RHP and LHP due to positive and negative values of the external magnetic field, respectively. In the above equation, the minus sign in ω_{le} refers to the magnetic field in $+B$ region for RHP, with $\varepsilon(\omega) = \varepsilon_2$ for region 2 having width d_2 , whereas the plus sign shows the magnetic field in $-B$ region for LHP, with $\varepsilon(\omega) = \varepsilon_1$ for region 1 having width d_1 . Now, the plasma and gyro frequencies are given by $\omega_p = \left(\frac{ne^2}{\varepsilon_0 m}\right)^{1/2}$ and $\omega_{le} = \frac{eB}{m}$, respectively. Here, m is electronic mass, e is electronic charge, n is the electron density, γ is effective collision frequency, and ω is the frequency of the incident EM wave in x -direction. To study the band structure characteristics of the EPPC, we plot dispersion curves and reflectance spectra using transfer matrix method (TMM) as discussed below.

5.2.2 Reflectance for Layered Media Using TMM

We now discuss the well-known TMM to calculate the reflectance of a layered periodic media considered as a 1D PC, as shown in Figure 5.2 (Yeh 1998; Kumar and Ojha 2008). If x -axis is chosen through the structure normal to the layers, the periodic refractive index profile can be defined as follows:

$$n(x) = \begin{cases} n_1, & 0 < x < d_1 \\ n_2, & d_1 < x < d \end{cases} \quad (5.3)$$

where $n(x+d) = n(x)$ and $d = d_1 + d_2$ is lattice period, where d_1 and d_2 are the thicknesses of the two regions having refractive indices n_1 and n_2 , respectively.

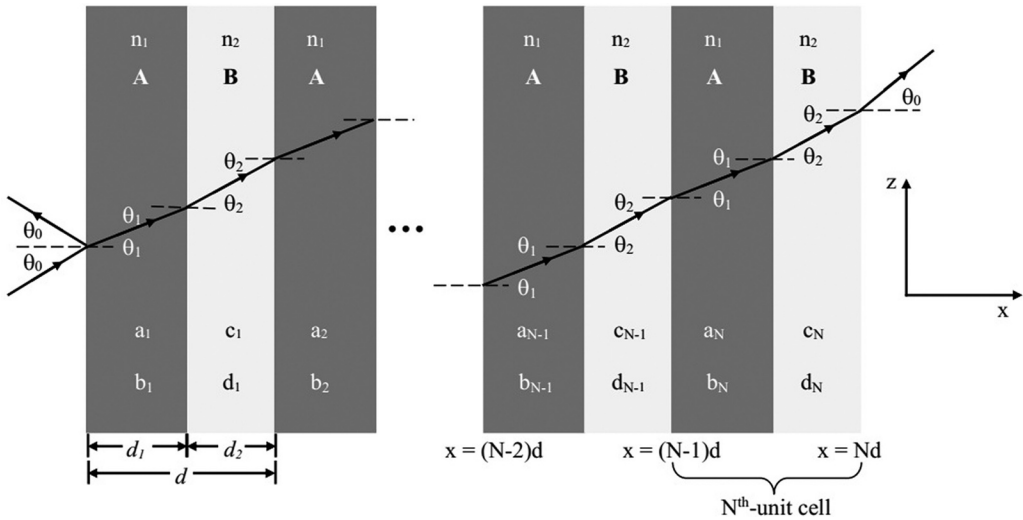


FIGURE 5.2

Periodic layered media with amplitudes of plane wave in successive layers along with unit cell.

For the spatial part of the EM Eigen mode, the 1D wave equation is given by the following:

$$\frac{d^2 E(x)}{dx^2} + \left[\left(\frac{\omega}{c} n \right)^2 - \beta^2 \right] E(x) = 0, \quad (5.4)$$

where β , ω , and c are the propagation constant, frequency, and velocity of light, respectively.

In this case, the electric field distribution $E(x)$ within each homogeneous layer can be expressed as the sum of an incident and reflected plane waves. Thus, the electric field in the n th unit cell is given by the following:

$$E(x) = \begin{cases} a_n e^{-ik_{1x}(x-nd+d_2)} + b_n e^{ik_{1x}(x-nd+d_2)}; & (nd-d) < x < (nd-d_2) \\ c_n e^{-ik_2(x-nd)} + d_n e^{ik_2(x-nd)}; & (nd-d_2) < x < nd \end{cases}, \quad (5.5)$$

where a_n , b_n , c_n , and d_n are the constants representing the amplitudes of incident and reflected plane waves in two layers A and B.

If an EM wave is incident along x -axis at an angle θ , it gets refracted with ray angles θ_1 and θ_2 in the successive layers, where $\cos \theta_1 = \left[1 - \left(\frac{1}{n_1} \right)^2 \sin^2 \theta \right]^{1/2}$ and $\cos \theta_2 = \left[1 - \left(\frac{n_1}{n_2} \right)^2 \sin^2 \theta \right]^{1/2}$.

Here propagation constants k_1 and k_2 depend on ω , ε , c , and the ray angles, as follows:

$$k_1 = \left[\left(\frac{\omega}{c} n_1 \right)^2 - \beta^2 \right]^{1/2} = \frac{n_1 \omega}{c} \cos \theta_1, \text{ and } k_2 = \left[\left(\frac{\omega}{c} n_2 \right)^2 - \beta^2 \right]^{1/2} = \frac{n_2 \omega}{c} \cos \theta_2, \text{ when it is assumed}$$

that the light is entered from air at oblique incidence θ , while for normal incidence $\theta = 0$, where $k_1/k_2 = \sqrt{\varepsilon_1/\varepsilon_2}$.

Using the matrix approach, the amplitudes a_n , b_n , c_n , and d_n of incident and reflected plane waves in two layers are related as follows:

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = D_1^{-1} D_2 P_2 \begin{pmatrix} c_{n-1} \\ d_{n-1} \end{pmatrix} \text{ and } \begin{pmatrix} c_{n-1} \\ d_{n-1} \end{pmatrix} = D_2^{-1} D_1 P_1 \begin{pmatrix} a_n \\ b_n \end{pmatrix},$$

where dynamical matrices, independent of layer thickness, for s -wave (TE) and p -wave (TM)

$$\text{are expressed as } D_j = \begin{pmatrix} 1 & 1 \\ n_j \cos \theta_j & -n_j \cos \theta_j \end{pmatrix} \text{ and } D_j = \begin{pmatrix} \cos \theta_j & \cos \theta_j \\ n_j & -n_j \end{pmatrix}, \text{ respectively,}$$

with $j = 1, 2$.

$$\text{Here, } P_1 = \begin{pmatrix} \exp(ik_1 d_1) & 0 \\ 0 & \exp(-ik_1 d_1) \end{pmatrix} \text{ and } P_2 = \begin{pmatrix} \exp(ik_2 d_2) & 0 \\ 0 & \exp(-ik_2 d_2) \end{pmatrix}.$$

Now, by simplifying the above relations, the amplitudes in layer A are related using the simple matrix multiplication method, and we obtain the following matrix equation:

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} a_n \\ b_n \end{pmatrix}, \quad (5.6)$$

in which the matrix elements are determined as follows:

$$m_{11} = e^{ik_1 d_1} \left[\cos k_2 d_2 + \frac{1}{2} i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2} \right) \sin k_2 d_2 \right], m_{12} = e^{-ik_1 d_1} \left[\frac{1}{2} i \left(\frac{k_2}{k_1} - \frac{k_1}{k_2} \right) \sin k_2 d_2 \right],$$

$$m_{21} = e^{ik_1 d_1} \left[\frac{1}{2} i \left(\frac{k_2}{k_1} - \frac{k_1}{k_2} \right) \sin k_2 d_2 \right], \text{ and } m_{22} = e^{-ik_1 d_1} \left[\cos k_2 d_2 - \frac{1}{2} i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2} \right) \sin k_2 d_2 \right].$$

Using the features of Bragg's reflector for the layered media, the coefficient of reflection of the structure can be derived by taking $r_N = \left(\frac{b_0}{a_0} \right)_{b_N=0}$, where a_0 and b_0 are the amplitudes of the incident plane wave in air and r_N is given by $r_N = \frac{CU_{N-1}}{AU_{N-1} - U_{N-2}}$, where $U_N = \frac{\sin(N+1)Kd}{\sin(Kd)}$, and N is a total number of unit cells.

Thus, the reflectance of the layered media considered as 1D PC is calculated using TMM as follows:

$$R_N = |r_N|^2 = \frac{|m_{21}|^2}{|m_{21}|^2 + (\sin Kd / \sin NKd)^2}, \quad (5.7)$$

where K is the Bloch wave number. This equation is employed for normal incidence $\theta = 0$, for which $k_1/k_2 = \sqrt{\epsilon_1/\epsilon_2} = n_1/n_2$, where TE and TM modes are not separated. In the case of TM mode for an oblique incidence, the matrix element m_{21} will be in the form: $m_{21} = e^{k_1 d_1} \left[-\frac{1}{2} i \left(\xi - \frac{1}{\xi} \right) \sin k_2 d_2 \right]$ with $\xi = \frac{k_1 \epsilon_2}{k_2 \epsilon_1}$.

5.2.3 Dispersion Relation

If the number of layers is too large, the dispersion relation can be obtained using transfer matrix as well as Bloch theorem used in Kronig-Penney model in solid-state physics. The matrix $\begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}$ given in Equation (5.6) will be unimodular as it relates incident and reflected amplitudes of plane waves in two layers and hence $m_{11}m_{22} - m_{12}m_{21} = 1$. Now using Floquet theorem, $E_K(x, z) = E_K(x)e^{-i\beta z}e^{-iKx}$, where $E_K(x+d) = E_K(x)$. Then, we get $\begin{pmatrix} a_n \\ b_n \end{pmatrix} = e^{-iKd} \begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix}$, where K is the Bloch wave number.

The dispersion relation between ω and K for the 1D PC can be derived from the eigen value of the transfer matrix $\begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}$ and can be written as follows:

$$K(\beta, \omega) = \frac{1}{d} \cos^{-1} \left[\frac{1}{2} (m_{11} + m_{22}) \right] \quad (5.8)$$

By simplification, for normal incidence along x -axis, the dispersion relation between ω and K can be expressed as follows:

$$\cos(Kd) = \cos(k_1d_1) \cos(k_2d_2) - \frac{1}{2} \left[\frac{k_2}{k_1} + \frac{k_1}{k_2} \right] \sin(k_1d_1) \sin(k_2d_2). \quad (5.9)$$

However, for TM mode in the case of oblique incidence, the dispersion relation between ω and K of 1D PC can be expressed as follows:

$$\cos(Kd) = \cos(k_1d_1) \cos(k_2d_2) - \frac{1}{2} \left[\xi + \frac{1}{\xi} \right] \sin(k_1d_1) \sin(k_2d_2), \quad (5.10)$$

where K is the Bloch wave number and $\xi = \frac{k_1\epsilon_2}{k_2\epsilon_1}$. This Equation (5.10) is used to plot the photonic band structure (PBS) in different cases at oblique incidences.

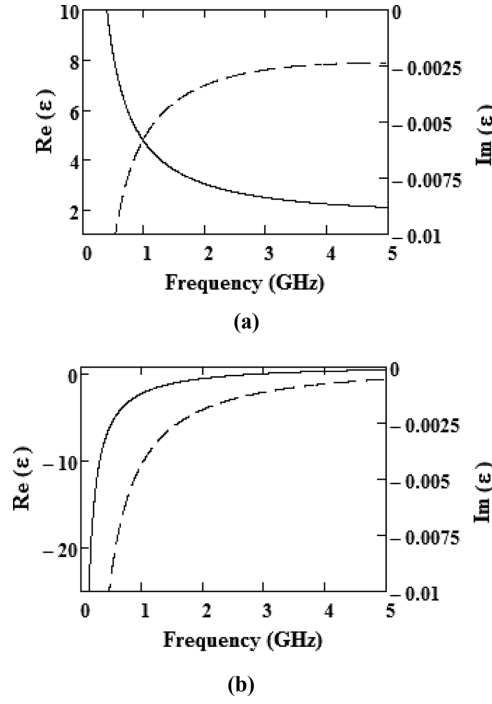
5.3 Results and Discussion

5.3.1 Specified Values of Parameters and Nature of Dielectric Constant

The effects of various parameters on the band structure and reflectance of the 1D EPPC, made of magnetized cold plasma, are analyzed by considering collision frequency $\gamma = 2 \times 2\pi \times 10^7$ Hz corresponding to plasma frequency $\omega_p = 8 \times 2\pi \times 10^7$ Hz. Here, $N = 30$ is considered in all cases while using Equation (5.7) for the calculation of reflectance. In band structure calculations, N is supposed to be infinite in using TMM along with Bloch theorem, where Equation (5.9) is used at normal incidence and Equation (5.10) is used at oblique incidence for p -wave.

Now, we plot the real and imaginary parts of dielectric constant ϵ for RHP with $B = 0.5$ T and LHP with $B = -0.5$ T using Equation (5.2) by taking electron density $n = 6 \times 10^{17}/\text{m}^3$ for a square wave-like magnetic field so that $d_1 = d_2 = 30$ mm. Here, calculations are made with the frequency of EM wave in GHz. The results are shown in Figure 5.3 for RHP and LHP. Comparing these curves, one can note that for RHP, $\text{Re}(\epsilon) > 0$, where the imaginary part represents the loss and its value is negative $\text{Im}(\epsilon) < 0$ and very small, which shows the plasma as a low-loss medium for the chosen parameters. In contrast, the dependence of dielectric constant for LHP is in reverse manner, where $\text{Re}(\epsilon) < 0$ and $\text{Im}(\epsilon) > 0$.

Thus, we find that such a PPC with specified values of collision frequency, plasma density, and the strength of the magnetic field acts as a low-loss medium in GHz frequency range. Therefore, TMM method can be used to calculate the reflectance, and the high reflectance (HR) range calculated using TMM should be analogous to the PBG calculated from the band structure. Therefore, we now study the effects of various parameters on the bandgaps of EPPC, which is assumed to be a low-loss medium with negligible absorption, for chosen values of the plasma density and collision frequency.

**FIGURE 5.3**

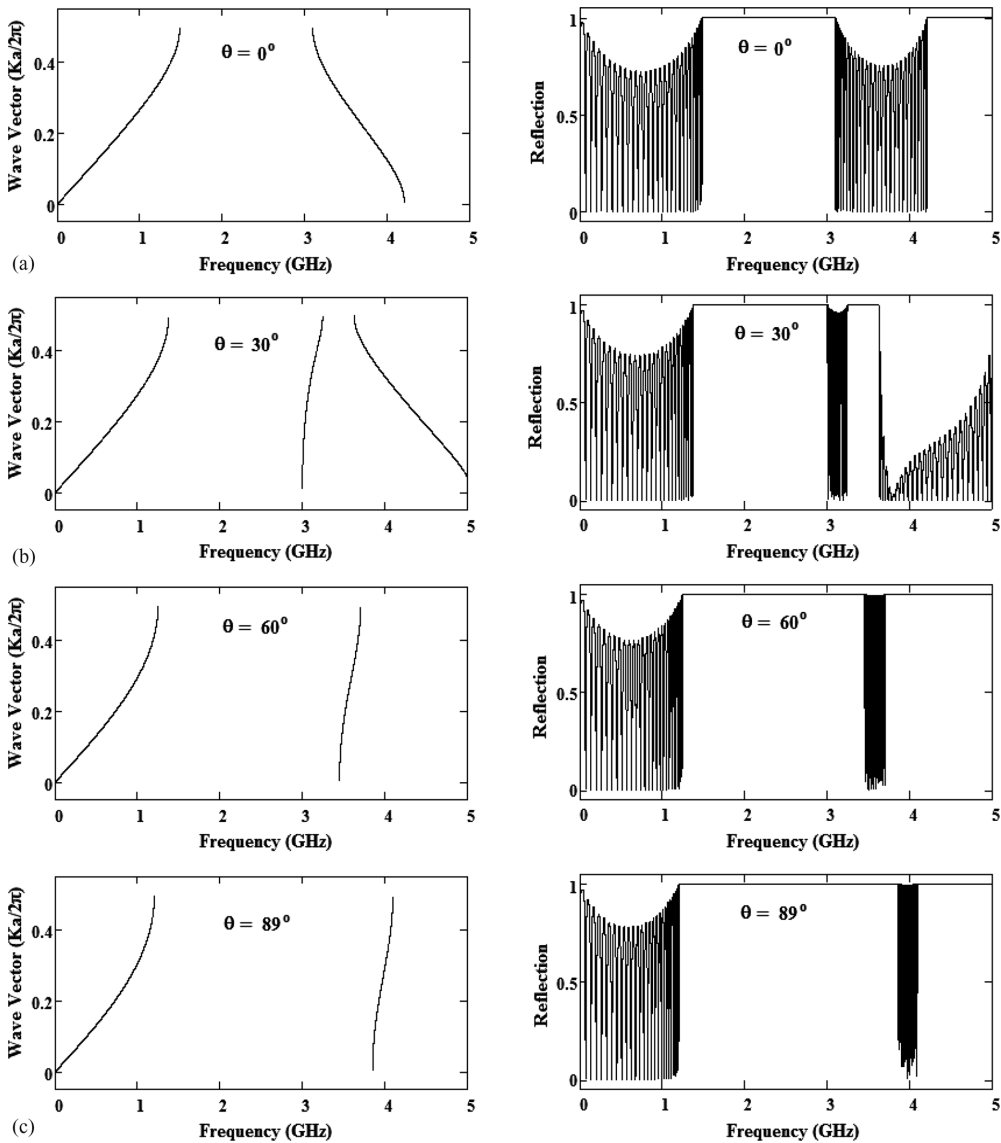
Real (solid line) and imaginary (dashed line) dielectric constants for (a) $B = 0.5$ T and (b) $B = -0.5$ T, with electron density $n = 6 \times 10^{17}/\text{m}^3$.

5.3.2 Effects of Various Parameters on Band Structure and Reflectance Spectra

The characteristics of band structure and reflectance spectra in EPPC are explained by varying the following parameters: angle of incidence, applied magnetic field strength, electron density, and layer thickness ratio. Band structure and reflectance spectra are plotted in different cases, and comparison is made between the obtained curves corresponding to each parameter. Therefore, the effects of these factors on PBGs of 1D EPPC are discussed hereafter.

5.3.2.1 Effect of Incident Angle (θ)

First, the effect of incident angle on PBG is analyzed by varying the incident angle as $\theta = 0^\circ, 30^\circ, 60^\circ$, and 89° , taking $n = 6 \times 10^{17}/\text{m}^3$ and $d = 60$ mm with $d_1 = d_2 = 30$ mm for a square wave-like periodic magnetic field taking $B = 0.5$ T. The reflectance spectra and PBS for the EPPC in the case of TM mode are plotted using Equations (5.7) and (5.10), respectively, using dielectric constants for RHP and LHP given in Equation (5.2). We compare the obtained curves at different incident angles shown in Figure 5.4 and found that HR frequency regions and PBGs observed from the band structures are in good agreement. It is inferred that as incident angle is increased at a constant magnetic field, the width of the PBG below plasma frequency decreases and further a new band appears near the plasma frequency, namely $8 \times 2\pi$ GHz when the incident angle is increased to $\theta = 30^\circ$, not shown in the figure (see Kumar et al. 2018b). The appearance of new gap for TM polarization at oblique incidence can be attributed to the Bragg's interference of splitted plasma layers.

**FIGURE 5.4**

Influence of incident angle on band structure and reflectance: (a) $\theta = 0^\circ$, (b) $\theta = 30^\circ$, and (c) $\theta = 60^\circ$, and $\theta = 89^\circ$, with $B = 0.5$ T; electron density $n = 6 \times 10^{17}/\text{m}^3$, and lattice parameter $d = 60$ nm.

If the incident angle is increased at a constant magnetic field, an additional obtained PBG is shifted toward low frequency, and the previously obtained gap decreases continuously, and with further increase in the incident angle above $\theta = 45^\circ$, the previously obtained band disappears, whereas there is enhancement in the new gap with increase in the incident angle. Similar changes are observed for different values of the magnetic field. Also, the newly appeared wide band is less dependent on the magnetic field while its width decreases slightly with an increase in the magnetic field. Thus, we find that the angle of incidence is a controlling factor for PBG exhibited by such an EPPC, and the PBGs are highly influenced by the incident angle.

5.3.2.2 Effect of Magnetic Field (B)

Furthermore, the influences of magnetic field on the band structure and reflectance spectra are studied for normal incidence with different values of the magnetic field as $B = 0.5$ T, 0.6 T, 0.7 T, and 0.8 T, with $n = 6 \times 10^{17}/\text{m}^3$ and $d = 60$ mm, where $d_1 = d_2 = 30$ mm for a square wave-like magnetic field. The obtained PBS and reflectance spectra are shown in Figure 5.5. Here, the HR regions and PBGs observed from the band structures are in good agreement. On increasing the strength of the applied magnetic field, the bandgap decreases, and the shifting in the lower band edge is more compared with the higher edge. Here the lower band edge of the wide band is shifted toward the higher frequency showing blue shift.

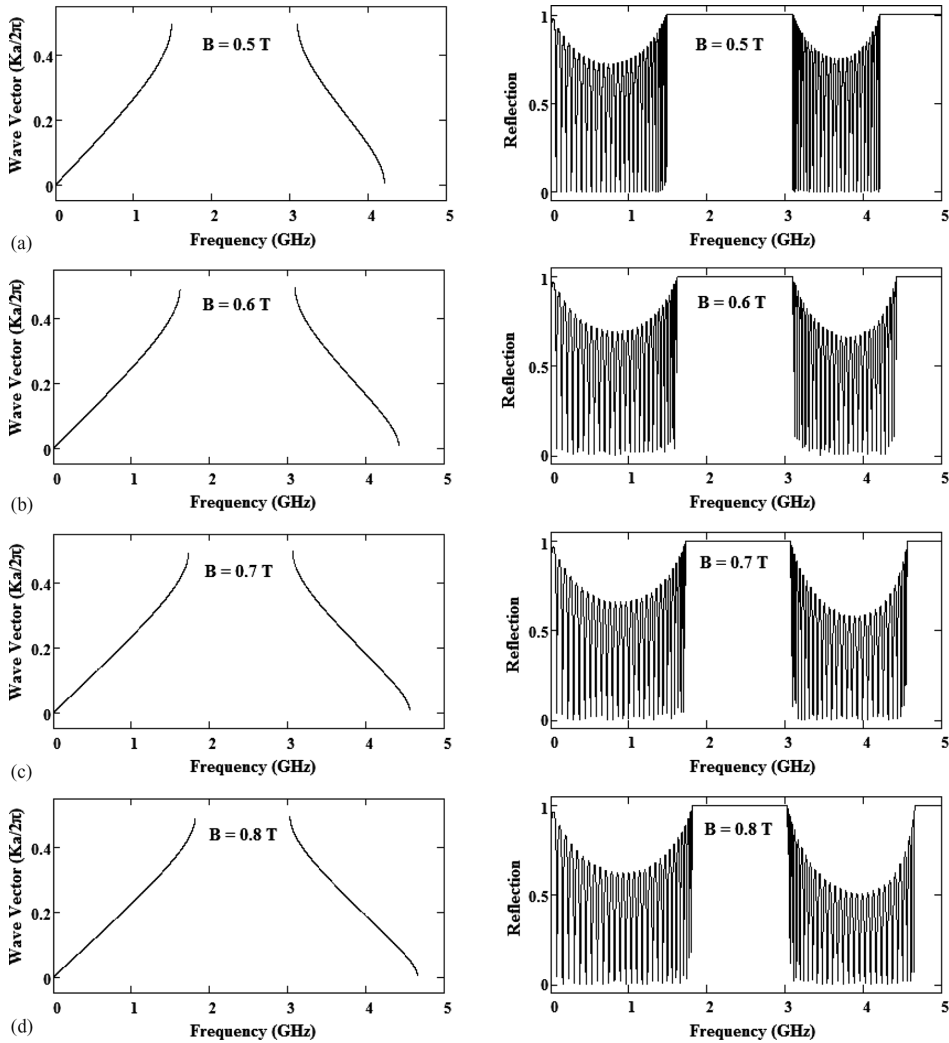


FIGURE 5.5

Influence of magnetic field on band structure and reflectance spectra at normal incidence for square-wave-like magnetic field: (a) $B = 0.5$ T, (b) $B = 0.6$ T, (c) $B = 0.7$ T, and (d) $B = 0.8$ T, with electron density $n = 6 \times 10^{17}/\text{m}^3$ and a lattice parameter $d = 60$ mm.

Thus, we observe that, for square wave-like magnetic field ($d_1 = d_2$), there is a bandgap below plasma frequency at normal incidence, which is wide for the smaller magnetic field, and the gap decreases with an increase in the magnetic field.

5.3.2.3 Effect of Electron Density (n)

Third, the effects of electron density on the band structure and reflectance spectra are studied for normal incidence by choosing different values of electron density as $n = 4 \times 10^{17}/\text{m}^3$, $6 \times 10^{17}/\text{m}^3$, $8 \times 10^{17}/\text{m}^3$, and $10 \times 10^{17}/\text{m}^3$ and $d = 60$ mm with $d_1 = d_2 = 30$ mm for a square wave-like periodic magnetic field. The band structures and reflection spectra are shown in Figure 5.6. By comparing the reflectance spectra and the band structures with different electron densities, one can note that the HR frequency ranges and PBGs observed from the

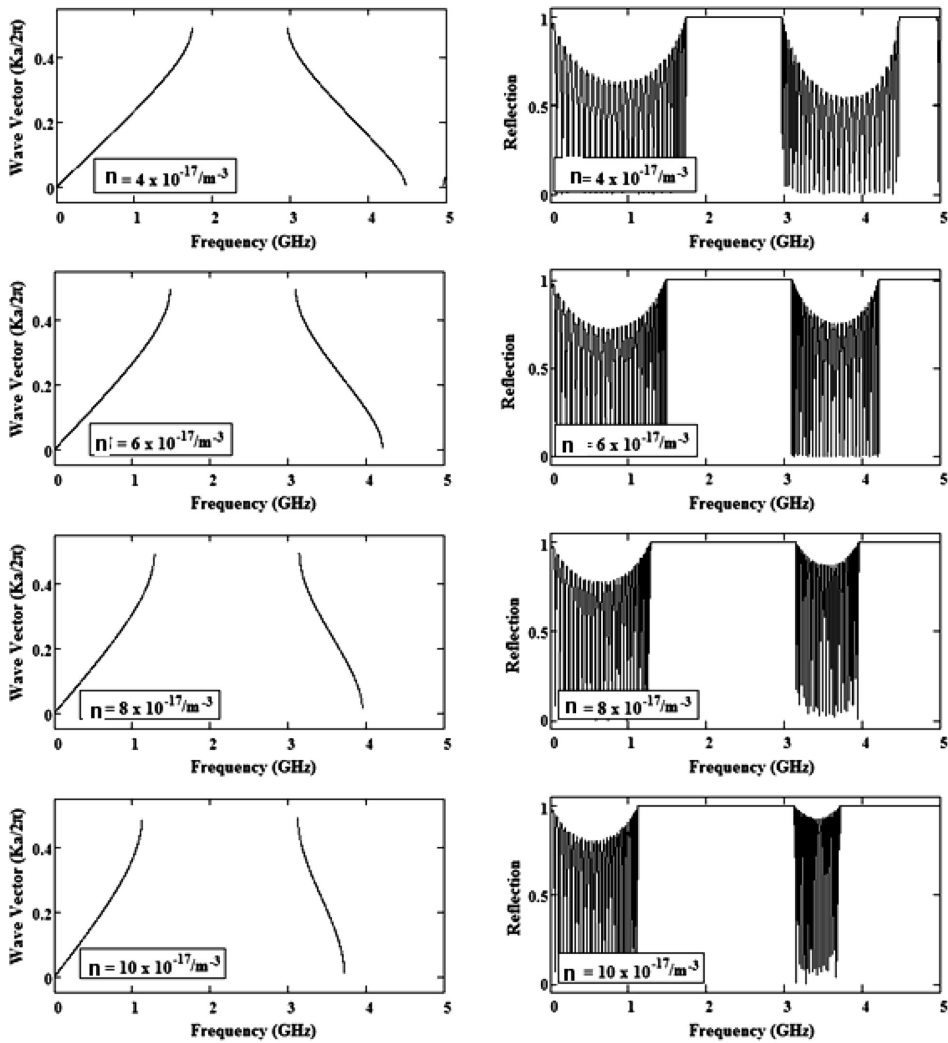


FIGURE 5.6

Influence of electron density on band structure and reflectance spectra at normal incidence with $B = 0.5$ T and lattice parameter $d = 60$ mm.

band structures are in good agreement. It is found that the PBG increases with increase in the electron density and again the lower band edge is more affected in comparison with the higher band edge.

5.3.2.4 Effect of Thickness Ratio (d_1/d_2)

Fourth, the impact of the thickness ratio on the band structure and reflectance spectra is determined by choosing $d_1/d_2 = 1, 2, 3$, and 4 (more than 1) for normal incidence with electron density $n = 6 \times 10^{17}/\text{m}^3$, $B = 0.5$ T, and lattice parameter $d = 60$ mm. Figure 5.7 shows the band structures and reflection spectra in various cases. It is again to note that

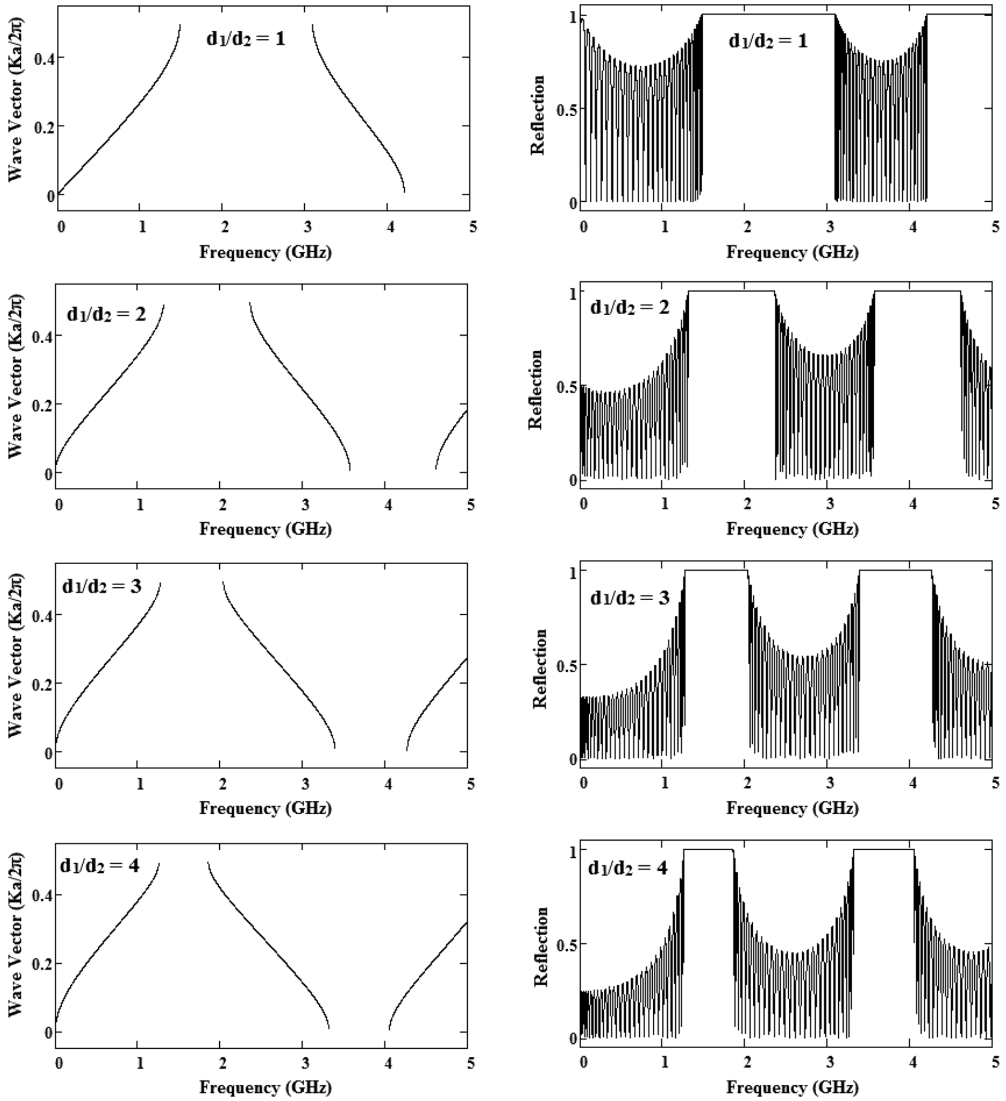


FIGURE 5.7

Influence of thickness ratio on band structure and reflectance spectra at normal incidence with $B = 0.5$ T, electron density $n = 6 \times 10^{17}/\text{m}^3$, and lattice parameter $d = 60$ mm.

the HR frequency ranges and PBGs observed from band structures are in good agreement. Comparing these curves, we may find that on increasing thickness ratio (greater than 1), bandgap decreases and is shifted toward the lower frequency side, that is, it shows a red shift. This is also observed that the number of forbidden bands increases with increase in the thickness ratio.

Furthermore, by decreasing the thickness ratio (less than 1), namely $d_1/d_2 = 1, 1/2, 1/3$, and $1/4$, it is found that the completely reflected band, that is, PBG, becomes narrow and a blue shift appears in the left band edge and red shift in the right band edge as shown in [Figure 5.8](#) for the same parameters, and consequently, the PBG is shifted

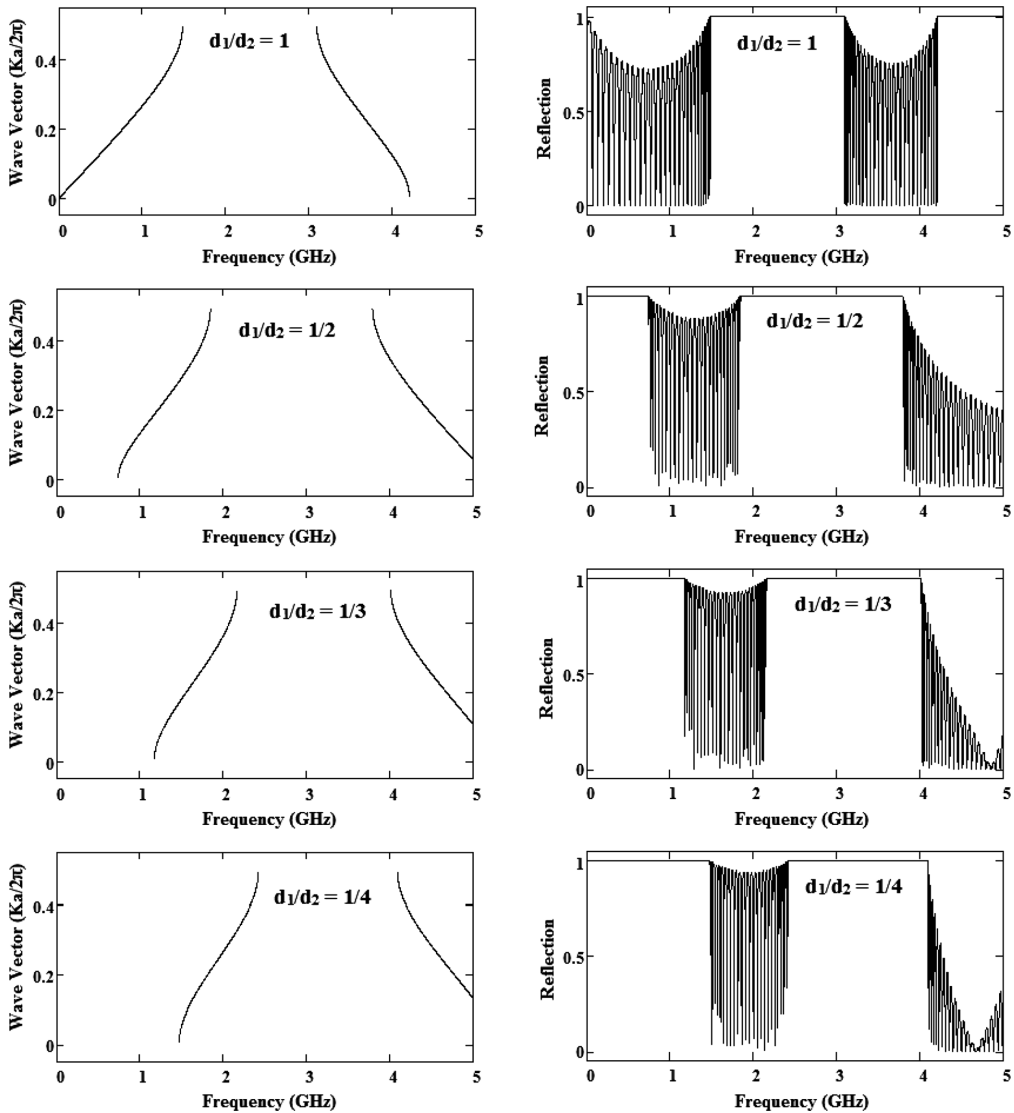


FIGURE 5.8

Influence of thickness ratio on band structure and reflectance spectra at normal incidence with $B = 0.5$ T, electron density $n = 6 \times 10^{17}/\text{m}^3$, and lattice parameter $d = 60$ nm.

toward the higher frequency showing a blue shift. Therefore, it reveals that if the thickness ratio is decreased, with value more than 1, the PBG increases, while there is reverse effect for thickness ratio less than 1, that is, bandgap also decreases if we decrease the thickness ratio.

Thus, based on the obtained results in various cases with different values of the affecting parameters: angle of incidence, applied magnetic field strength, electron density, and layer thicknesses ratio, it has been noticed that the PBGs of such an EPPC are not only affected by varying these parameters but also the position of the bands as well as number of bands in the GHz frequency range. Thus, it can be summarized that these parameters act as controlling factors tailoring the PBGs of the EPPC in the GHz range. This analysis will be very much useful in designing tunable broadband reflectors and filters.

5.4 Conclusion

In this chapter, the photonic bands exhibited by a 1D EPPC have been described using bulk magnetized cold plasma. The periodic existences of RHP and LHP are due to positive and negative values of external magnetic field of magnetized cold plasma, respectively. Using the well-known simple TMM, the band structure and reflectance spectra in the induced periodic plasma crystal are theoretically analyzed by varying the parameters such as angle of incidence, applied magnetic field strength, electron density, and layer thicknesses ratio. By plotting and comparing the reflectance spectra and PBSs in different cases, it is observed that the HR frequency regions and PBGs observed from the band structures are in good agreement. It is noticed that with increase in the angle of incidence, there is enhancement in the PBG, and thereafter a new band appears near the plasma frequency as angle is increased to $\theta = 30^\circ$, and the appearance of such a new gap for TM polarization at oblique incidence can be attributed to the Bragg's interference of plasma layers. On increasing the applied magnetic field strength, PBG decreases, where shifting in the lower band edge is more significant compared with the higher band edge. Moreover, it is found that the PBG enhances with increase in the electron density and again the lower band edge is more sensitive in comparison with the higher band edge. If we increase the thickness ratio, the PBG decreases and shows a red shift; in contrast, there is a reverse effect on decreasing the thickness ratio (less than 1), the PBG becomes narrow and is shifted toward the higher frequency showing a blue shift. In conclusion, the impact of variations of these parameters results in tailoring photonic bands of the EPPC. Such observed results provide important insights for designing a tunable broadband reflector in the desired lower and higher frequency ranges in GHz and may be very important in sensors, optical filters, switching applications, couplers, and designs of other tunable photonic devices.

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6

Broadband Fiber-Optic Parametric Amplifier Based on Near-Zero Ultraflat Dispersion Photonic Crystal Fiber

Partha Sona Maji

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6.1 Introduction

Different novel photonic crystal fiber (PCF) architectures have been investigated for various applications since its first realization around 1996 by Knight et al. which are not possible with the conventional step-index or graded-index fiber by Knight (2003) and Russel (2006). They are special types of fiber with air hole running across the cross-section in a hexagonal manner. The unique properties, such as controllability of dispersion and superior nonlinearity with wide-band single-mode behavior by Knight (2003), Kuhlmeier et al. (2003), and Russel (2006), have made PCF an effective choice for specific applications, which are difficult to be realized with conventional waveguides by Kuhlmeier et al. (2002, 2003) and Dudley and Taylor (2009). For example, the conversion efficiency of four-wave mixing (FWM), an underlying mechanism for achieving broadband fiber optic parametric amplifier (FOPA), can be significantly improved with the dispersion

engineered PCFs by tailoring the phase-matching condition as shown by Agrawal (2007). Dispersion profile such as ultraflat near-zero nature could further be exploited for high-gain and broadband parametric amplifications that depend on efficient FWM applications. Recently, Maji (2015a) has shown amplification property of flat dispersion profiles with three zero-dispersion wavelengths (ZDWs). However, for practical purposes, three pump conditions could not be applied simultaneously. At a particular instance, only one ZDW could be targeted, and thereby amplification performance could only be available corresponding to that ZDW only. Also, the flatness of the dispersion profile was compromised to accommodate three ZDWs. Simultaneously, the wider ZDWs (second and third) cease to exist for slightly higher-temperature environment by Maji (2015b). As the present Dense Wavelength Division Multiplexing (DWDM) system requires an increase of information capacity, thereby needs amplifiers with uniform gain along with the wider bandwidth to compensate the loss of fiber and equalize the power of the various channels, a wider bandwidth with uniform gain is always in demand.

Although dispersion can be tuned for specific applications, however, controlling dispersion for a wider wavelength range with all uniform air-hole diameters has been a difficult task. Few of the major architects in designing the ultraflat dispersion profile are triangular doped core by Hansen (2003) or different core geometries by Florous et al. (2006) and Saitoh et al. (2006) or different types of air holes and the submicron size of air holes in the cladding of the fiber by Poletti et al. (2005), Saitoh and Koshiba (2004), Saitoh et al. (2003), and Wu and Chao (2005). However, the technology in realizing the ultraflat nature precisely is not easily feasible with the present-day fabrication technology. Selective liquid technology technique (Eggleton et al. 2011; Kerbage and Eggleton 2002; Maji et al. 2014; Sasaki et al. 2002; Witkowska et al. 2006; Yiou et al. 2005; Yu and Liou 2009) is an alternative for the above issue as the mismatch in the optimized dispersion profile can always be compensated with different types of available liquids while fine tuning the profile for a change of temperature of the system.

The present chapter uses the selective liquid infiltration technique for designing a near-zero ultraflat dispersion profile with single ZDW with all uniform air-hole diameters in the cladding around the communication wavelength (Maji and Das 2017). Further, the technique has been applied toward a broadband FOPA. We could optimize an ultraflat dispersion profile with $D = 0 + 1$ ps/nm/km for a bandwidth of 316 nm with all equal air-hole diameter in the cladding using this technique. The phase-matching condition of optimized PCF has been used to carry out the parametric amplification after establishing the gain and bandwidth dependence on the fiber length, pump power, and operating wavelength. Our numerical investigation reports that with a proper choice of pump, we can achieve wide bandwidth FOPA source more than 220 nm around the communication wavelength.

6.2 Theory of Parametric Amplifier and Analysis Method

Basic mechanism leading to the amplification in the degenerate FWM process is the conversion of two pump photons of frequency ω_p into a signal photon ($\omega_s < \omega_p$) and an idler photon ($\omega_i > \omega_p$) satisfying the energy conservation relation ($2\omega_p = \omega_s + \omega_i$), where the subscripts "s," "i," and "p" stands for signal, idler, and pump, respectively. For the efficient

FWM, and a consequent high gain and wide bandwidth of FOPA demands a certain phase-matching condition is satisfied between the pump and the signal and the idler.

The optical parametric gain G_s by Agrawal (2007) and Marhic (2008) is calculated using the equation given below:

$$G_s = 1 + \left(\frac{\gamma P}{g} \right)^2 \sin^2(gL), \quad (6.1)$$

where γ is the effective nonlinear coefficient given by $\gamma = 2\pi n_2 / \lambda A_{\text{eff}}$, with n_2 is the nonlinear refractive indices, P is the input pump power, A_{eff} is the effective area, and g is the parametric gain coefficient given by Equation (6.2) as follows:

$$g = \sqrt{(\gamma p)^2 - \left(\Delta k / 2 \right)^2} \text{ where } \Delta k = 2\gamma P / \Delta k_L, \quad (6.2)$$

Δk_L is the linear phase-mismatch term $\Delta k_L = \Delta\beta + \Delta k_W$. The waveguide phase-mismatch term Δk_W can be neglected for single-mode fibers by Agrawal (2007); considering up to the fourth order, $\Delta\beta$ can be written as follows:

$$\Delta\beta = \beta_2 (\Delta\omega)^2 + \frac{1}{12} \beta_4 (\Delta\omega)^4, \quad (6.3)$$

where $\Delta\omega$ is the frequency shift ($\Delta\omega = \omega_p - \omega_s = \omega_i - \omega_p$) and β_2 and β_4 are the second and fourth order of dispersion parameter given by $\beta_2 = -\frac{\lambda^2}{2\pi c} D$ and $\beta_4 = \frac{\partial^2}{\partial \omega^2} \beta_2$, respectively, with D is the chromatic dispersion parameter, which is given as follows:

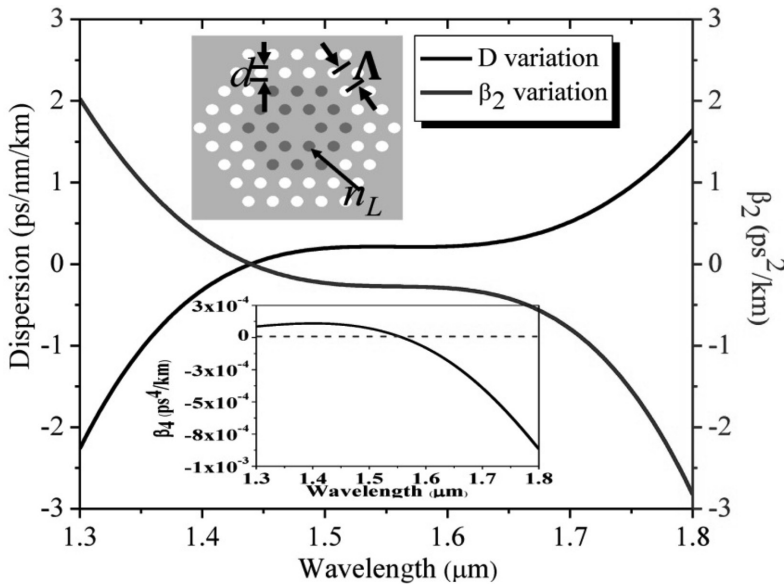
$$D = -\lambda/c d^2 \text{Re}[n_{\text{eff}}] / d\lambda^2, \quad (6.4)$$

where $\text{Re}[n_{\text{eff}}]$ is the real part of effective indices obtained from simulation and c is the velocity of light in vacuum.

For the net FOPA gain, the linear phase-mismatch term $\Delta\beta$ must be negative with the sufficient magnitude to balance the nonlinear contributions, that is $\Delta\beta$ should satisfy the condition of $-4\gamma P \leq \Delta\beta \leq 0$. For the perfect phase matching in Equation (6.2), the value of Δk becomes zero, which in turn corresponds to the maximum signal gain, hence, $\Delta\beta = -2\gamma P$ with $g_{\text{max}} = \gamma P$.

6.3 Schematic Design of the Investigated “PCF”

The schematic of investigated PCF is shown in the top inset of Figure 6.1 with a silica background with two inner air-hole rings infiltrated with the liquid of chosen refractive index. For the ease of fabrication, the air-hole diameter is kept constant throughout the structure. The modal fields associated with the dispersion and nonlinear properties are investigated using a multipole method-based solver CUDOS MOF utilities (CUDOS MOF).

**FIGURE 6.1**

Optimized dispersion profile with $D = 0 + 1$ ps/nm/km over a wavelength range of 316 nm and corresponding β_2 variation. Top inset: Cross-section of the optimized design. Bottom inset: corresponding fourth-order GVD parameter (β_4), which remains positive till the wavelength value of 1558 nm.

6.4 Numerical Results and Discussion

Designing near-zero and ultraflat PCF for the communication wavelength is a task with optimization of multiparameters such as air-hole diameter (d), hole-to-hole distance (Δ), and liquid Refractive Index (RI) (n_L). The detailed investigation of the dependence of individual parameters on total dispersion and its slope is described in the following sections.

6.4.1 Design and Optimization Procedure

Regular PCFs, consisting of air holes arranged in a hexagonal nature, offer dispersion values, which are mainly governed by certain parameters. First, the air-hole diameter: for the smaller air-hole diameter, the waveguide dispersion effect is lower, and the dominating effect towards the total dispersion is the background material dispersion. Second, the number of air-hole rings around the core: the smaller number of rings of air holes shows less influence on the total dispersion and vice versa. However, it should be noted that after a certain number of the air-hole rings, dispersion becomes almost constant, provided other parameters are unchanged. Third, the distance between hole to hole (or pitch) plays a major role in determining the overall dispersion: the larger the pitch value, the higher is the material dispersion and vice versa.

We have considered a selective liquid infiltration technique for this case. We have an additional parameter for the optimization of the ultraflat near-zero dispersion with this technique, which is the RI of the infiltrating liquid. Designing near-zero and ultraflat PCF for communication wavelength is a task with the optimization of multiparameters

such as air-hole diameter (d), hole-to-hole distance (Λ), and liquid RI (n_L). Initially, we consider a liquid that has a constant wavelength-independent refractive index. However, the wavelength dependence of the fiber background material (silica glass here) is taken into account, and the refractive index of silica glass is calculated using the Sellmeier formula throughout the study. Using artificial liquid prevents the exceptional computation of choosing a proper liquid out of many available index-matching liquids, which leads to certain optimization of the parameters and results in approximate values of the parameters that can be used for practical realization. When a practical liquid is selected, we re-optimize the fiber structure by proper adjustment of Λ and d to have ultraflat near-zero dispersion profile with single ZDW.

6.4.2 Steps of Optimization

The procedure is performed in three steps. In the *first* step, we show the effect of varying one of the design parameters on the dispersion curve while the rest are kept constant, which gives information about the sensitivity of the variation of the parameter toward the total dispersion. In the *second* step, we kept one of the parameters fixed (value obtained from the first step) and optimized the other parameters. Once one parameter is optimized, we re-optimize the design by adjusting other parameters. In the *third* step, we select a practical oil (wavelength-dependent RI) close to the optimized RI and optimize the other parameters to achieve an ultraflat near zero dispersion with single ZDW.

6.4.2.1 First Step of Optimization

1. Effect of Λ toward D

The present section shows the *first* stage of the design optimization as follows. Figure 6.2 shows the effect of Λ on the D values. For this case, we have kept the air-filling fraction (d/Λ) and liquid RI constant. It can be clearly observed that the total dispersion changes without drastic change in its slope around the communication wavelength window. Increasing the value of pitch increases the dispersion curve without significantly modifying the slope.

2. Effect of Liquid RI (n_L) toward D

We investigate the variation of dispersion properties for a change of infiltrating liquid RI in Figure 6.3. Hence, we have kept the hole-to-hole distance (Λ) and air-filling fraction (d/Λ) constant. From the figure, it can be observed that both the magnitude and slope of D are affected for different values of n_L . Both the dispersion and its slope are modified when the refractive index of the liquid is varied. Increasing the air-hole diameter d increases the negative slope of the dispersion without significantly modifying the dispersion value.

3. Effect of Liquid Air-Hole Diameter (d) toward D

The effect of varying the air-hole diameter d is shown in Figure 6.4. Also increasing d has the effect of increasing the negative slope of the dispersion without significantly modifying the dispersion value.

Thus, the effect of *varying the Λ influences the total dispersion*, whereas d has the desired effect of modifying the dispersion slope, and varying n_L modifies both the dispersion and its slope as shown by Gundu et al. (2006).

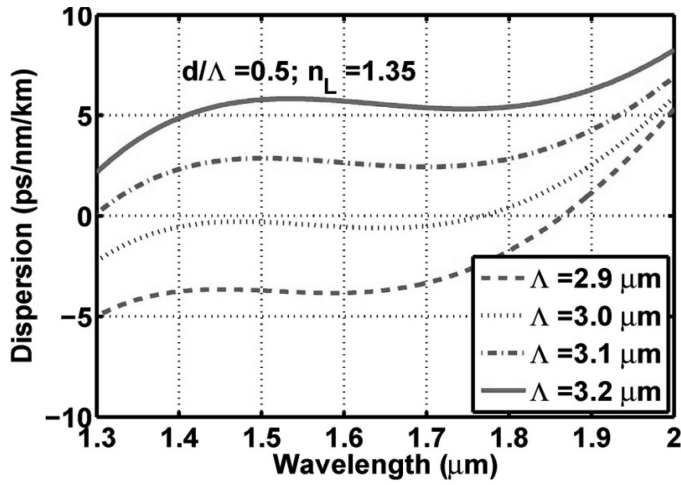


FIGURE 6.2

Variation of the D parameter as a function of hole-to-hole distance (Λ) keeping air-filling fraction (d/Λ) and liquid RI (n_L) fixed.

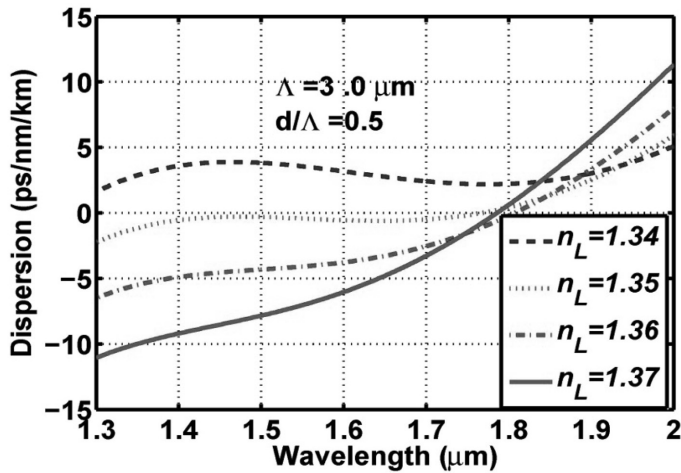


FIGURE 6.3

Variation of the D parameter as a function of liquid RI (n_L) keeping air-filling fraction (d/Λ) and hole-to-hole distance (Λ) fixed.

6.4.2.2 Second Step of Optimization: Optimization with Artificial Liquid

Then, we started the *second* stage of the optimization procedure. Starting from arbitrary parameters (we choose $n_L = 1.34$, $\Lambda = 3.0 \mu\text{m}$, and $d = 1.60 \mu\text{m}$), the value of n_L is varied progressively till we obtain a flat dispersion although not necessarily near zero. Then we successively change Λ and d either to raise or lower the dispersion or to modify its slope. Following the above steps, we obtained the ultraflattened near zero dispersion with single ZDW as shown in Figure 6.5 with $D = 0 \pm 1.00$ ps/nm/km for a 356 nm wavelength range (from 1408 to 1764 nm).

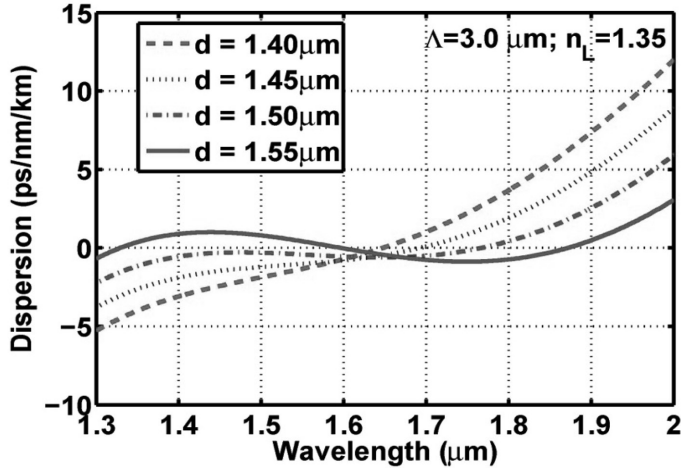


FIGURE 6.4

Variation of the D parameter as a function of air-hole diameter (d) keeping hole-to-hole distance (Λ) and liquid RI (n_L) fixed. Increasing the air-hole diameter d increases the negative slope of the dispersion without significantly modifying the dispersion value.

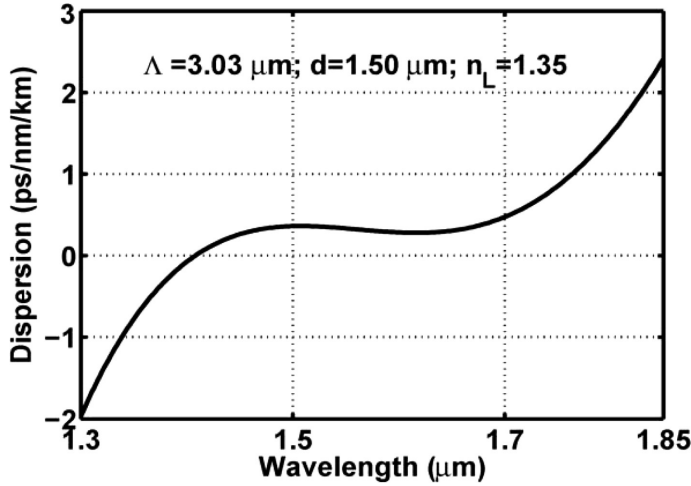


FIGURE 6.5

Optimized ultraflat dispersion with single ZDW over the wavelength region 1408–1764 nm (wavelength span 356 nm) with $D = 0 + 1.00$ ps/nm/km with a hypothetical liquid of index 1.35.

6.4.2.3 Third Step of Optimization: Optimization with Practical Liquid

We continue with the *third* optimization stage using a preliminary design with an artificial dispersion-less liquid. We select a liquid (calling it as Liquid#1) whose RI is nearer to 1.35 in the considered wavelength range and is given by Cauchy equation (Equation 6.5) from M/s Cargille Ltd. (<http://www.cargille.com>).

$$n = 1.352751400 + \frac{254675}{\lambda^2} - \frac{1.024360 \times 10^{11}}{\lambda^4}, \quad (6.5)$$

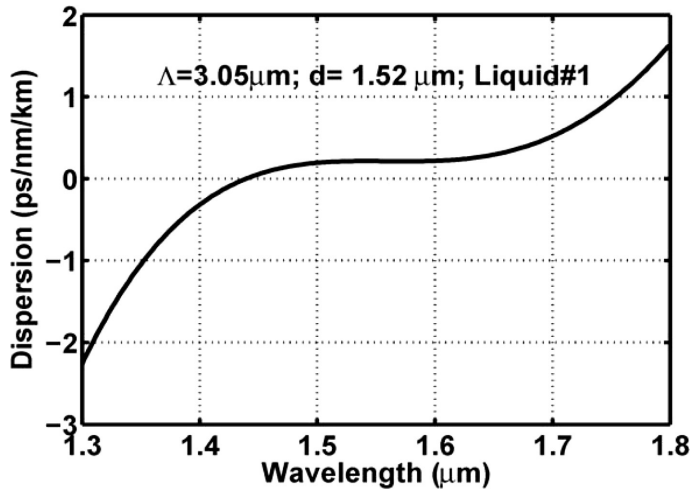


FIGURE 6.6

Optimized dispersion profile with practical liquid with $D = 0 + 1.00$ ps/nm/km for 316 nm (1440–1756 nm) wavelength range with $\Lambda = 3.05$ μm and $d = 1.52$ μm with liquid #1.

where λ is in $\text{\AA}$. Following the above optimization procedure as shown in the previous sections, we further adjust the pitch and air-hole diameter value to reach at Figure 6.6 with $D = 0 + 1.00$ ps/nm/km for 316 nm (1440–1756 nm) wavelength range with $\Lambda = 3.05$ μm and $d = 1.52$ μm for the above liquid with a propagation loss of $\sim 10^{-3}$ dB/m. The value of the ZDW has been found to be 1440 nm for the above case. The corresponding variations of the higher-order Group Velocity Dispersion (GVD) parameter of β_2 are shown in Figure 6.1, while the variation of β_4 is shown in the bottom inset of Figure 6.1, respectively. It is interesting to note that the value of β_4 remains positive till 1558 nm of wavelength.

6.4.3 Parametric Gain Dependence around ZDW

Proper FOPA performance depends on the phase matching condition (pump condition) and the dispersion profile of the working fiber. FOPA gain and bandwidth dependence are discussed for a change of fiber length, pump power, and pump wavelength (λ_p).

The simulation for FOPA gain and bandwidth has been carried out using Equation (6.1). The required parameters of nonlinear coefficient (γ) and parametric gain coefficient (g) are calculated as an initial step to determine FOPA gain. The parameter “ g ” and the phase-mismatch factor term is evaluated per Equation (6.2), and the values of higher-order dispersion parameter, which is required to calculate phase-mismatch term $\Delta\beta$, are estimated according to Equation (6.3). The values of β_2 and β_4 are estimated from the chromatic dispersion parameter (D).

6.4.3.1 Effect of Fiber Length

FOPA gain and bandwidth for a variation of fiber length around the ZDW are shown in Figure 6.7 for a pump power of 10 W and input λ_p at 1450 nm for an anomalous pumping. The FOPA gain increases with the fiber length; however, the bandwidth decreases due to the increase of phase mismatch for the longer fiber. Moreover, matching of phase for an increased value of fiber length is broken due to longitudinal chromatic dispersion

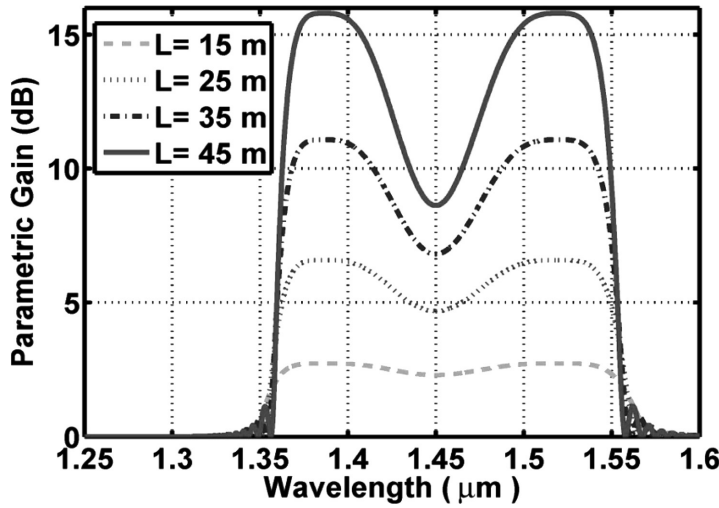


FIGURE 6.7

FOPA gain and bandwidth variation as a function of fiber length for a fixed pump power of 10 W.

fluctuation along the fiber length by Chatterjee et al. (2014). Consequently, a fiber length of 30–40 m will serve the purpose of wider bandwidth of the FOPA. As the studied fiber is having propagation loss of $\approx 10^{-3}$ dB/m, the aforementioned length contributes only negligible loss for the signal propagation.

6.4.3.2 Effect of Pump Power

FOPA gain for the pump power variation is shown in Figure 6.8 for 35 m of fiber length at $\lambda_p = 1450$ nm. It can be clearly observed that the gain and the bandwidth increases as a function of the pump power. However, the pump power necessarily needs to be optimized

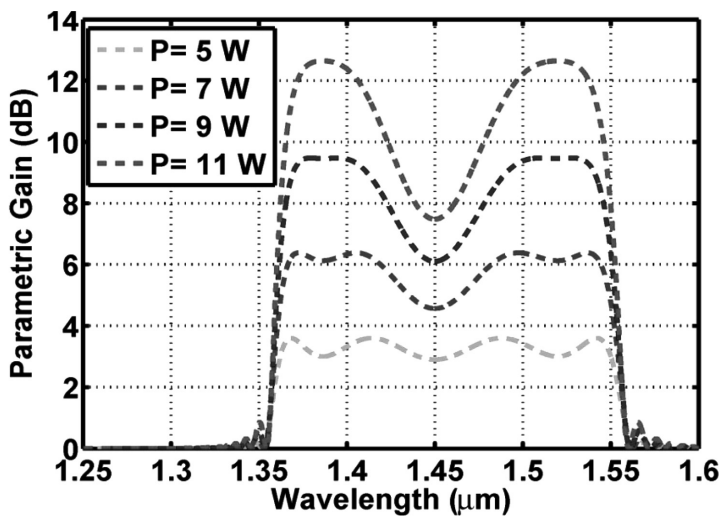


FIGURE 6.8

FOPA gain and bandwidth variation as a function of pump power (P) for 35 m fiber length at $\lambda_p = 1450$ nm.

for suppressing nonlinear effects such as stimulated Raman scattering. In order to study the consequence of the above nonlinear effects, Raman threshold (R_{Th}) has been computed in our FOPA configuration. Considering Raman gain coefficient for silica $\sim 10^{-13}$ m/W (Agrawal 2007), the calculations show R_{Th} to be ≈ 150 W (with a propagation length of 35 m), and accordingly a pump power of ≈ 12 W will not be sufficient to induce any Raman effect. In a different note, the input intensity corresponding to the above pump power of optimized fiber is ≈ 40 MW/cm². The value is much less than the R_{Th} of 0.6 GW/cm² (Agrawal 2007) ensuring no impact of Raman scattering.

6.4.3.3 Effect of Pump Wavelength

FOPA gain spectrum and the associated phase-mismatch term $\Delta\beta$ for a variation of λ_p with a pump power of 10 W and fiber length of 40 m are shown in Figure 6.9a and b, respectively. Improved phase matching and consequent superior FOPA gain with wider bandwidth are achieved around smaller anomalous pumping (i.e., $\beta_2 \leq 0$) pumping having a positive β_4 as

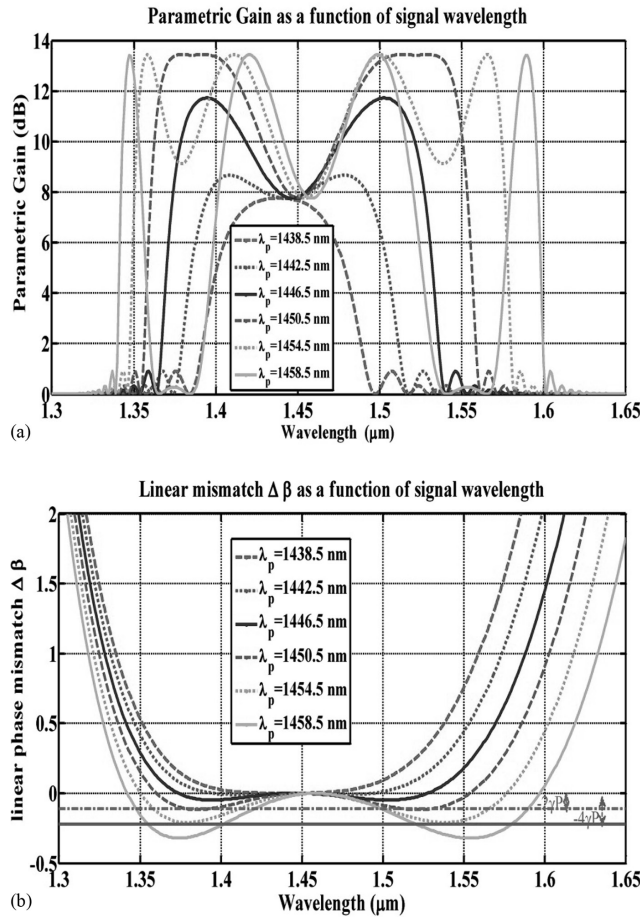


FIGURE 6.9

(a) FOPA gain and bandwidth variation as a function of pumping wavelength for pump power of 10 W and fiber length of 40 m around ZDW; (b) phase-mismatch ($\Delta\beta$) alteration corresponding to (a). The phase-mismatch curve clearly predicts the dip and peak of FOPA gain spectrum.

shown by Chatterjee et al. (2014). Bottom inset of Figure 6.1 shows the optimized PCF having a positive β_4 around ZDW (up to 1558 nm). Since the optimized PCF is having flat dispersion close to zero value; the pumping condition can be tuned further from ZDW toward anomalous region (with marginal alteration in negative β_2 values) for an improved phase matching and consequent wider bandwidth with adequate FOPA gain. Such tunable pump source can be achieved by outcoupling the signal in an optical parametric oscillator (OPO) with proper value of grating period and operating temperature (Shukla et al. 2016). Consequently, ultraflat nature of the optimized dispersion profile imparts an additional advantage where tuning of pump wavelength adds an additional degrees of freedom toward achieving high gain and wider spectrum, which is explained in Figure 6.4 as follows. We started our investigation with a normal dispersion pumping at 1438.5 nm (remember ZDW = 1440 nm) as presented with the red curve (longer dotted line). It can be observed that the $\Delta\beta$ lies well above (actually positive) the gain criteria of $-4\gamma P \leq \Delta\beta \leq 0$ (Figure 6.9b and results in a very small gain and narrow bandwidth (curve corresponding to $\lambda_p = 1438.5$ nm of Figure 6.9a). Moving toward a small anomalous pumping ($\lambda_p = 1342.5$ and 1346.5 nm), the $\Delta\beta$ variation is negative; however, it is yet to reach the maximum gain criteria of $\Delta\beta = -2\gamma P$ and results in smaller gain and narrower bandwidth, however, better than the normal pumping one ($\lambda_p = 1338.5$ nm). Moving further at $\lambda_p = 1350.5$ nm, the value of $\Delta\beta$ remains around $-2\gamma P$ for relatively wider wavelength resulting in almost a flat (variation is less than 1%) gain spectra both in the idler and the signal part around 1370–1400 and 1505–1535 nm, respectively. It is interesting to observe that the wider spectrum with the maximum gain could be achieved for $\lambda_p = 1354.5$ nm as $\Delta\beta$ remains nearer to the favorable phase-mismatch condition of $-4\gamma P \leq \Delta\beta \leq 0$ and the maximum gain took place at $\Delta\beta = -2\gamma P$ for a tuning of λ_p away from the ZDW.

This is primarily a consequence of near-zero ultraflat nature of the dispersion profile with negligible change in β_2 . So, broadband FOPA gain is achievable for $\Delta\beta$ lying closer to $-2\gamma P$ and the above finds practical realization by incorporating proper choice of the pumping condition, which can be seen in Figure 6.9a and b for the gain and phase-mismatch curve, respectively. Tuning λ_p further at 1458.5 nm, we can observe $\Delta\beta$ remain outside of the permissible limit of $-4\gamma P \leq \Delta\beta \leq 0$, and this results in a narrower bandwidth. However, $\Delta\beta$ values $-2\gamma P$ around 1590 nm (upper wavelength of the spectrum) and 1340 nm (lower wavelength of the spectrum) for wider wavelengths for the same λ_p , resulting sharper peaks about these wavelengths, which can be clearly found from Figure 6.9a and b, respectively. So, the bandwidth decreases, but we can realize new peaks on either sides of the central spectrum far from the pump with a wide tuning from ZDW. The above nature is interesting as we can realize narrow peaks very far from λ_p with a proper choice of pump condition. Thus, phase matching curve dictates completely on the nature of the gain and bandwidth spectra of the FOPA performance. This principle of achieving wider FOPA gain with a positive β_4 at a smaller anomalous pump condition can be applied for achieving high gain with wider spectrum by means of appropriate engineering of the waveguide geometry.

6.4.4 Optimized Gain Spectrum of the Near-Zero Ultraflat Dispersion

Based on the FOPA gain and bandwidth variation for a change of fiber length, pump power, and pump wavelength, we optimized an FOPA gain spectrum as shown in Figure 6.10 with $P = 8.5$ W, 35 m long fiber at $\lambda_p = 1453.7$ nm. A wideband spectrum having a 3 dB bandwidth of 223 nm from 1352 to 1575 nm with a peak gain of 8.7 dB has been achieved. The equivalent phase-mismatch term has been shown in the inset of Figure 6.10. The phase-mismatch curve clearly predicts the dip and peak of FOPA gain spectrum where proper gain took place in the range of $-4\gamma P \leq \Delta\beta \leq 0$ and peak gain took place for $\Delta\beta = -2\gamma P$.

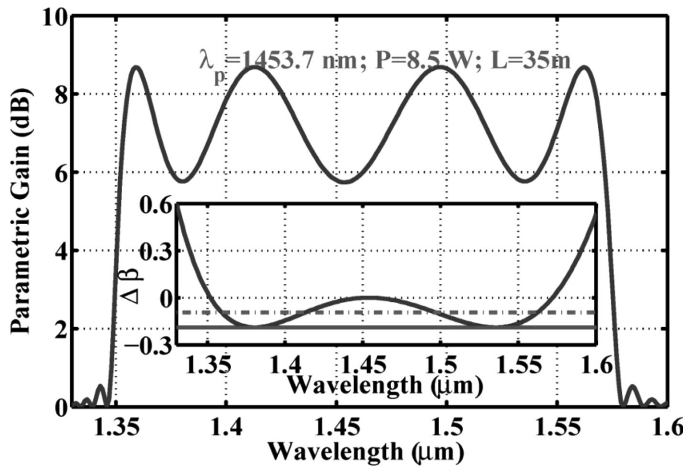


FIGURE 6.10

Optimized parametric gain spectrum for a bandwidth of 223. Inset: Corresponding $\Delta\beta$ variation. Net gain took place for $-4\gamma P \leq \Delta\beta \leq 0$ while maximum gain corresponds to $\Delta\beta = -2\gamma P$.

6.5 Discussion and Conclusion

Finally, this work presents the realization of a parametric amplifier based on dispersion engineered near-zero ultraflat profile with selective liquid infiltration. We could optimize a dispersion profile with $D = 0 + 1.00$ ps/nm/km for a wavelength band of 316 nm with $\Lambda = 3.05$ μm and $d = 1.52$ μm and a practical liquid having a refractive index of 1.35 with a ZDW of 1440 nm. The relatively larger PCF parameters ensure that the optimized design can be used in practice. The parametric gain and bandwidth have been investigated in detail for a variation of PCF length, pump power, and pump wavelength. It has been observed that increasing the length of the fiber increases FOPA gain with reduced bandwidth, while an increment of pump power leads to increment of the gain and bandwidth simultaneously. Pump wavelength dependence on FOPA gain and bandwidth show some unique outcomes. Investigation also reveals that an appropriate alteration of the pump wavelength improves FOPA gain bandwidth by means of favorable higher-order dispersion parameters having $\beta_2 \leq 0$ and positive β_4 around ZDW. Based on the variation of FOPA gain and bandwidth for a change of fiber length, pump power, and pump wavelength (λ_p), our numerical analysis established an optimized FOPA gain bandwidth of more than 220 nm around ZDW.

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Properties of Electromagnetic Density of Mode in Acoustically Perturbed Photonic Crystal

Ayush Aman, Yogesh Sharma, Surendra Prasad, and Vivek Singh

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7.1 Introduction

The photonic crystal (PC) is a composite structure with a periodic arrangement of high and low refractive index materials in one dimension (1D), two dimensions (2D), and three dimensions (3D). John (1987) and Yablonovitch (1987) have proposed this structure for the first time. Since its advent, the researchers around the world have tried to investigate the various properties exhibited by the crystal, among which is the photonic bandgap (PBG) for a certain range of electromagnetic (EM) frequencies for which propagation is prohibited through the PC structure. The existence of PBG leads to many interesting phenomena such as modification of spontaneous emission (SE) (Yablonovitch 1987) and photon localization (John 1987). It has been reported that the SE is proportional to the EM density of mode (DOM) by Fermi's Golden rule (Heitler 1984). Using the knowledge of DOM of a PC, the emission and absorption properties of an atom or molecules embedded in PC cavities can be determined. Modifications of emission and absorption properties of the atom or molecules therein play a main role in fabricating optoelectronic devices such as micro laser and optical memories. As PC shows PBG for certain range of frequencies, the DOM can be suppressed within this PBG, thereby inhibiting SE. The lasing threshold of laser and decay rate of dipole emitter can be reduced using this property. It has also been reported that tuning

of EM DOM near bandgap edges finds various applications in band-edge SE enhancement in layered semiconductors (Dowling et al. 1994; Tocci et al. 1996), nonlinear optical effects such as gap solitons (deSterke and Sipe 1990), bistability (Acklin et al. 1993), limiting and switching (Scalora et al. 1994a), and thin-film isolator (Scalora et al. 1994b).

PCs fabricated using recent techniques are static, which means that their optical properties are fixed during the fabrication. These PCs have to be reconfigured when the frequency regime is changed. Many people have tried to tune the PC in different ways. The PC can be tuned by changing the permittivity or permeability or periodicity of the dielectric materials constituting the PC by thermal field (Wild et al. 2004), electric field (Du et al. 2004; Weiss et al. 2005), magnetic field (Xu et al. 2003), and acoustic field (Park and Lee 2004).

Here in this chapter, we addressed acousto-optic (AO) effect, which is used to tailor the EM DOM. The chapter is organized as follows. In the first section, we have briefly introduced the PC, methods, and applications of tuning the PBG. The second section deals with the AO effect. The detail of the hypothetical structure and the equations used to calculate the DOM are discussed in the third section. In the latter sections, we have shown the results obtained and finally the conclusions.

7.2 AO Effect

AO effect has been used to control light signals for many years. Light intensity and polarization are influenced by AO effects (Gnewuch et al. 2000), which deal with the interaction of optical waves with the acoustic waves in material media. Such an interaction was first predicted by Brillouin in 1922, and later in 1932, it was experimentally verified by Debye and Sears in the United States and by Lucas and Biguard in France. The interesting phenomenon associated with the interaction of light with sound waves is the diffraction of light by the acoustically perturbed medium. When the acoustic waves propagate in a medium, there is an associated strain field, which results in a change in the index ellipsoid of medium, called the photo-elastic effect. This effect in a material couples the mechanical strain to the optical index of refraction and changes the refractive index of the material, which is described as follows:

$$\Delta\eta_{ij} = \Delta\left(\frac{1}{n^2}\right)_{ij} = p_{ijkl}S_{kl}, \quad (7.1)$$

where $\Delta\eta_{ij}$ is the optical impermeability tensor and S_{kl} is the strain tensor. The coefficients p_{ijkl} form the strain-optic tensor. The index ellipsoid of a crystal in the presence of an applied strain field is given as follows:

$$(\eta_{ij} + p_{ijkl}S_{kl})x_ix_j = 1 \quad (7.2)$$

As η_{ij} and S_{kl} are symmetric tensors, the indices i and j as well as k and l can be permuted. Thus in contracted indices, equation with respect to change in refractive index becomes

$$\Delta\left(\frac{1}{n^2}\right)_{ij} = p_{ij}S_j, \quad i, j = 1, 2, \dots, 6, \quad (7.3)$$

where S_j are strain components. The equation of index ellipsoid in the presence of strain field can now be expressed as follows:

$$\begin{aligned}
 & x^2 \left(\frac{1}{n_x^2} + p_{11}S_1 + p_{12}S_2 + p_{13}S_3 + p_{14}S_4 + p_{15}S_5 + p_{16}S_6 \right) \\
 & + y^2 \left(\frac{1}{n_y^2} + p_{21}S_1 + p_{22}S_2 + p_{23}S_3 + p_{24}S_4 + p_{25}S_5 + p_{26}S_6 \right) \\
 & + z^2 \left(\frac{1}{n_z^2} + p_{31}S_1 + p_{32}S_2 + p_{33}S_3 + p_{34}S_4 + p_{35}S_5 + p_{36}S_6 \right) \\
 & + 2yz(p_{41}S_1 + p_{42}S_2 + p_{43}S_3 + p_{44}S_4 + p_{45}S_5 + p_{46}S_6) \\
 & + 2zx(p_{51}S_1 + p_{52}S_2 + p_{53}S_3 + p_{54}S_4 + p_{55}S_5 + p_{56}S_6) \\
 & + 2xy(p_{61}S_1 + p_{62}S_2 + p_{63}S_3 + p_{64}S_4 + p_{65}S_5 + p_{66}S_6) = 1,
 \end{aligned} \tag{7.4}$$

where n_x , n_y , and n_z are the principal indices of refraction. The form of p_{ij} can be derived from the symmetry of the crystal. The point-group symmetry dictates that the 36 coefficients are zero, as well as relations that exist between the nonvanishing coefficients. The elasto-optic coefficients in contracted notation for a cubic crystal are of the following form:

$$\begin{pmatrix} P_{11} & P_{12} & P_{21} & 0 & 0 & 0 \\ P_{21} & P_{11} & P_{12} & 0 & 0 & 0 \\ P_{11} & P_{21} & P_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & P_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & P_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & P_{44} \end{pmatrix} \tag{7.5}$$

The readers can refer to the book written by Yariv and Yeh (1983) for further reading.

7.3 Theory and Modeling

We have considered a 1D PC, which is formed by a series of periodic units that can be described as $(AB)^N$, where A and B denote the two different layers with different refractive indices, and N is the total number of layers in this PC. The thickness of each layer is chosen such that $n_A d_A = n_B d_B = \lambda/4$, as in a typical quarter wave stack, where n_A , n_B , d_A , and d_B are the refractive indices and thicknesses of A and B layers, respectively, and λ is the free space wavelength. The crystal structure formed by such a periodic arrangement does not allow propagation of a finite range of wavelength centered around λ , thus forming 1D PBG, because of which light propagating in this PC finds index mismatch, resulting in Bragg reflection at each interface of A and B layers. They interfere constructively at the backward direction for certain wavelength, which corresponds to a PBG and causes a strong reflection. When acoustic wave gets coupled with the PC, it induces variable strain, which changes the index and also breaks the structural periodicity of the original PC. Thus, the band structure change is expected.

Here, in this chapter, we have considered a longitudinal acoustic wave traveling along the z -axis, which is normal to layer boundaries. The deformation (u) caused by the acoustic wave (Qian et al. 2009) can be represented as follows:

$$u(z, t) = U \cos(\Omega_s t + k_s z), \quad (7.6)$$

where U , Ω_s , and k_s are the maximum displacement amplitude, angular frequency, and the wave vector of acoustic wave, respectively. The strain (S) induced by acoustic wave can be obtained by differentiating Equation (7.6):

$$S(z, t) = k_s \cdot U \sin(\Omega_s t + k_s z). \quad (7.7)$$

The thickness (d) of all the A and B layers, which change due to strain, can be given as follows:

$$d = d_z + d_z S(z, t). \quad (7.8)$$

Here, d_z represents the original thickness. The longitudinal strain due to the acoustic wave changes the elliptical sphere of refractive index (ESRI) (Ma et al. 2008). Also, it is described in the above section. The equation of ESRI is given as follows:

$$(B_{ij}^0 + \Delta B_{ij})x_i x_j = 1 \quad (i, j = 1, 2, 3). \quad (7.9)$$

Here, x_i denotes the component of the Cartesian coordinate, B_{ij}^0 the coefficient of ESRI without any stress, and ΔB_{ij} the variation of the coefficient of ESRI when stress acts on the elastic media. ΔB_{ij} is produced by the variation of media densities caused by stress and obeys Hooke's law. Considering the symmetries of the media, ΔB can be simplified to 6×1 matrices and photoelastic coefficient tensor p can be simplified to 6×6 matrices. With these simplifications, Hooke's law can be re-expressed as follows:

$$\Delta B_i = p_{ij} S(z, t) \quad (i, j = 1, 2, 3, \dots, 6). \quad (7.10)$$

Using Equations (7.7), (7.9), and (7.10), we may deduce the change in the refractive index Δn . The change in the refractive index (Δn_z) along the z -axis is given as follows:

$$\Delta n_z = -\frac{1}{2} n_z^3 p_{11} S(z, t). \quad (7.11)$$

Here, n_z and p_{11} represent the original refractive index and the photoelastic coefficient, respectively. From Equations (7.8) and (7.11), it is clear that the thickness and refractive index of each layer change periodically. These changes are static to EM wave as its speed is much larger than the speed of acoustic wave. Thus, we are able to reconfigure the PC at any certain moment and calculate the time resolved band structure, transmission properties, and EM DOM, for an acoustically perturbed PC.

Different approaches have been developed for calculating DOM. D'Aguzzo et al. (2004) have given a method to compute the DOM, which includes the Green function technique. Quasinormal-mode treatment has been used to investigate DOM in the PC by Settini et al. (2003). Bendickson et al. (1996) has developed an exact analytical expression for N-lattice 1D PC through the Wigner phase time approach. We have used Wigner phase time approach, which is widely used to compute the DOM for a finite periodic

structure. According to this approach, the transmittance coefficient (t) of the structure can be written as follows:

$$t \equiv x + iy = \sqrt{T} e^{i\varphi}. \quad (7.12)$$

Here, x and y are the real and imaginary parts of the transmission coefficient, respectively, and $\varphi = \tan^{-1} \frac{y}{x}$. Also, φ is the total phase accumulated as the EM waves propagate through the structure and hence can be written as kd , where k is the effective wave number, and d is the physical thickness of the structure. So we have

$$\tan kd = \frac{y(\omega)}{x(\omega)}. \quad (7.13)$$

Now, DOM can be obtained by differentiating Equation (7.13) with respect to ω , and hence

$$\rho(\omega) \equiv \frac{dk}{d\omega} = \frac{1}{d} \frac{y'x - x'y}{x^2 + y^2}, \quad (7.14)$$

where x' and y' are derivatives of x and y with respect to ω , respectively. Here, $\rho(\omega)$ is the DOM, which is defined as the total number of wave number available per unit frequency range.

In order to calculate the transmission coefficient (t), we have used transfer matrix method (TMM) (Yariv and Yeh 1983), which is widely used to study the optical properties of layered media. According to TMM, the final matrix of the structure can be written as follows:

$$M = \prod_{j=1}^k \begin{bmatrix} \cos \delta_j & \frac{i}{N_j} \sin \delta_j \\ i \cdot N_j \sin \delta_j & \cos \delta_j \end{bmatrix} = \prod_{j=1}^k M_j = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (7.15)$$

Here, $\delta_j = (\omega/c)\eta_j d_j \cos(\theta_j)$ is the phase delay in the j th layer, where d_j is the effective thickness of the j th layer. The optical admittance (N_j) is expressed as $N_j = \eta_j \cos(\theta_j)$ (for s -wave) and $N_j = \eta_j / \cos(\theta_j)$ (for p -wave), and η_j and θ_j are the refractive index and propagating angle in the j th layer, respectively. The transmission coefficient (t) is given as follows:

$$t = \frac{2 \cdot \eta_0}{\eta_0 m_{11} + m_{21} + \eta_0 \eta_{k+1} m_{12} + \eta_{k+1} m_{22}}. \quad (7.16)$$

Here η_0 and η_{k+1} are the refractive indices for incoming medium and outgoing medium, respectively. These values are given as $\eta_0 \cos(\theta_0)$ and $\eta_{k+1} \cos(\theta_s)$ for s -wave and $\eta_0 / \cos(\theta_0)$ and $\eta_{k+1} / \cos(\theta_s)$ for p -wave. Here θ_0 is the incident angle, and θ_s represents the ray inside the outgoing medium. The transmittance is given as $T = (\eta_{k+1} / \eta_0) t t^*$.

7.4 Results and Discussion

In our study, we have considered a 1D PC, which is formed by a series of periodic arrangement of hydrogen-loaded UV-unexposed and UV-exposed SiO₂. It has been reported that the hydrogen-loaded SiO₂ has an improved photosensitivity and its refractive index changes at an order of 10⁻³ after UV exposure (Erdogan et al. 1994; Guan et al. 2000), and the PC structure after UV exposure is still treated as a uniform acoustic medium. The thickness of

each layer is chosen such that $n_A d_A = n_B d_B = \lambda/4$, where $n_A = 1.46$, $n_B = 1.465$, $d_A = 265.4$ nm, and $d_B = 264.5$ nm are the refractive indices and thicknesses of A and B layers, respectively. Here, $\lambda = 1550$ nm is the free space wavelength, which is considered as optical window for many optical applications due to low loss in this range of wavelength. Longitudinal acoustic waves of different frequencies are launched to perturb the periodicity and the refractive index of the PC. A particular frequency of 21 MHz, for which the wavelength of acoustic wave (265 μ m), is equal to the total physical length of the unperturbed PC, is selected, and then EM wave having normalized angular frequencies $\omega / \omega_0 \cong 0.994$ to 1.006 is made to incident into the perturbed PC. DOM is calculated using Equation (7.14). It is assumed that all the materials are nonmagnetic in nature, and the whole structure is embedded in air. We have normalized our angular frequencies range with the central angular frequency (1.2161×10^{15} rad/s), which corresponds to the central wavelength (1550 nm). It is common convention to express DOM in a dimensionless quantity. So, we have normalized the DOM with the velocity of light (c) in free space.

In Figure 7.1a, we have shown the schematic of the considered PC. To check the effect of acoustic wave on the considered structure, acoustic waves with different frequencies are made to incident onto the structure (Figure 7.1b). As it can be seen that the magnitude of DOM, for 42, 63, and 84 MHz, is high at right edge, whereas for 21 MHz frequencies, it shows different behaviors. This effect is much visible away from bandgap at which $\omega/\omega_0 \approx 1$. We have

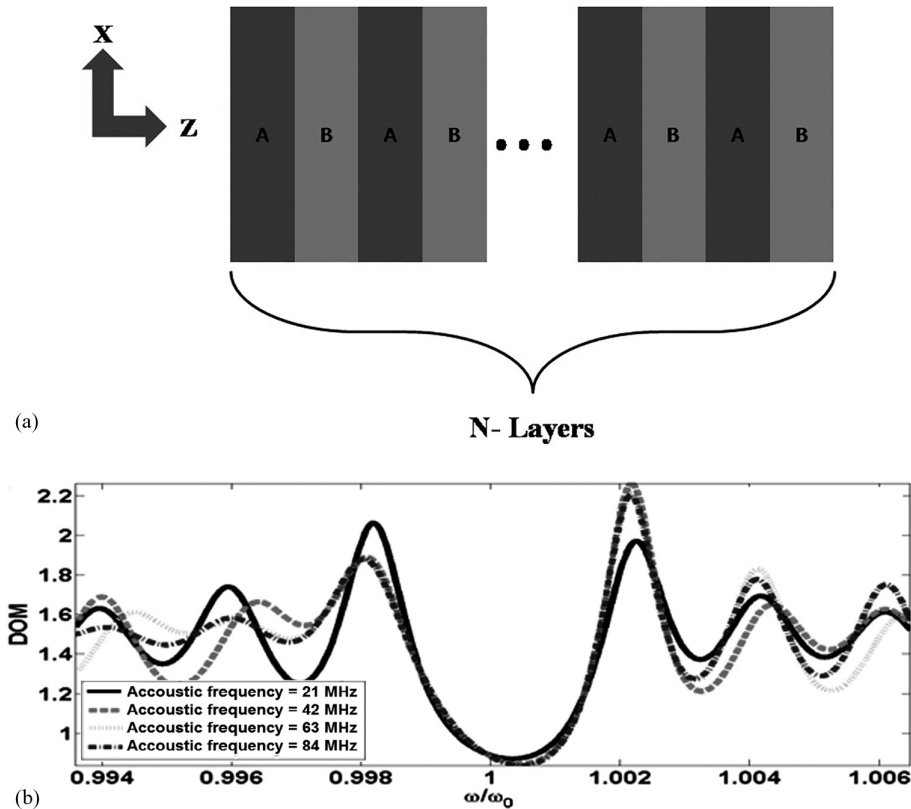


FIGURE 7.1

(a) Schematic of the considered PC with $N = 1000$ layers. (b) The DOM corresponding to different acoustic frequencies.

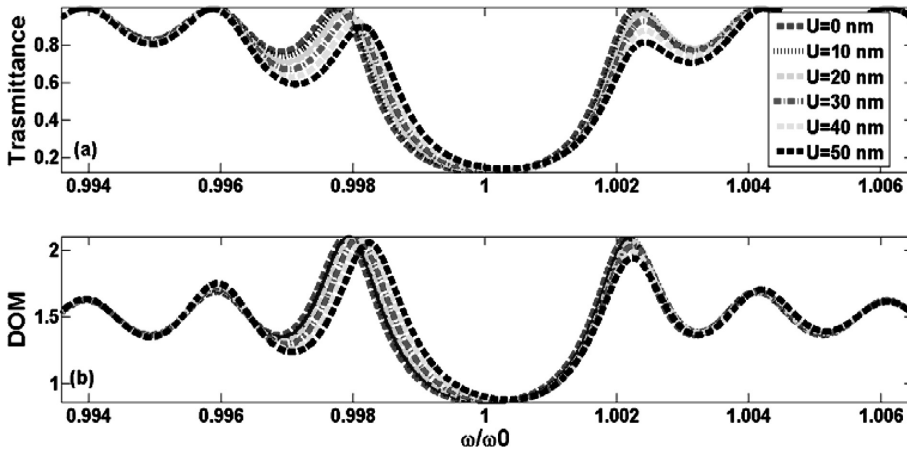


FIGURE 7.2

Transmittance and dimensionless DOM versus normalized frequency at different acoustic amplitudes.

selected a particular frequency 21 MHz for further investigation because at this frequency, the acoustic wavelength is equal to the thickness of the considered PC, that is, 265 μm .

The transmittance and the DOM are plotted in Figure 7.2. It can be seen that the shape of the DOM resembles the transmittance curve. The effect of acoustic amplitude on the DOM is also shown in Figure 7.2. It has been found that, with the increase in the acoustic amplitude from 0 to 50 nm in steps of 10 nm, the magnitude of the DOM has gradually decreased at both the edges, while it has increased at the mid gap region. To make it more clear, Figure 7.3a and c and b are plotted separately for each edges and mid gap region. However, it is interesting to notice that, at a particular angular frequency ($\omega = 1.214 \times 10^{15}$ rad/s) near the left edge, the magnitude of DOM has increased with increase in acoustic amplitude, which is shown in Figure 7.3d.

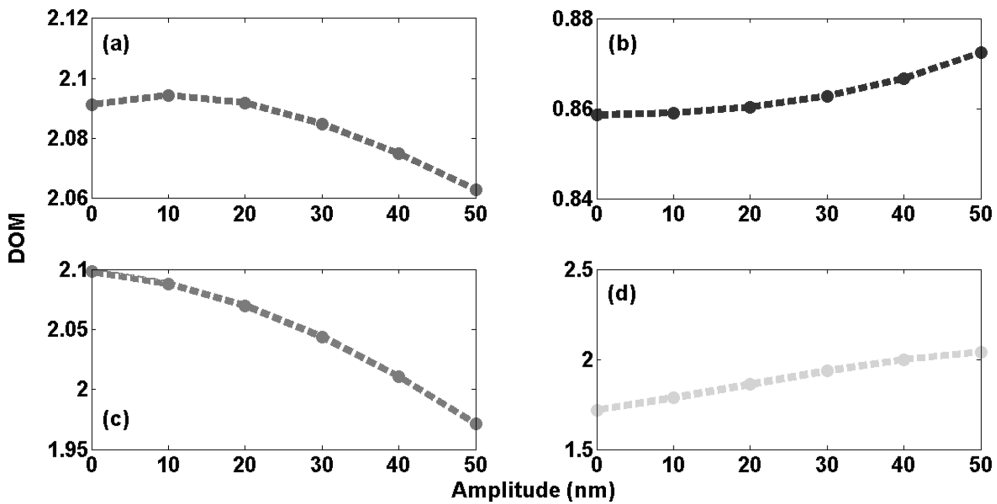


FIGURE 7.3

The variation of DOM at the (a) left edge, (b) mid gap, and (c) right edge at $\omega = 1.2142 \times 10^{15}$ rad/s (d) with varying acoustic amplitude.

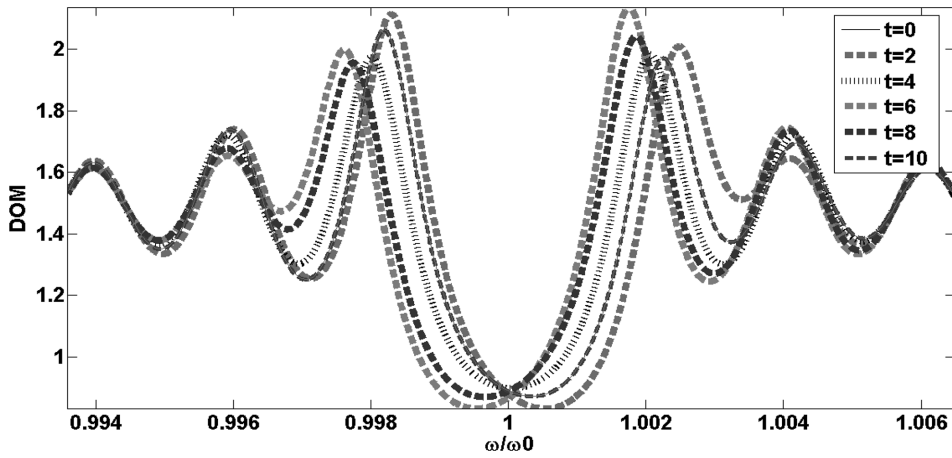


FIGURE 7.4

Acoustic wave induced center frequency swing at different moments.

Further, we examine the trend of DOM at different instants of time. For this, we have divided the time period of the acoustic wave into 10 equal intervals. The bandgap and the magnitude of DOM show a periodic swing from the central frequency with a fractional change in acoustic time period as shown in Figure 7.4. From Figure 7.4, it can be seen that the magnitude of DOM at the lower frequency is larger than that at the higher frequency side at certain instant ($t = 0, 2$), and at some other instants ($t = 6, 8$), the DOM at lower frequency is smaller than that at higher frequency. Figure 7.5 is plotted to show the nature of DOM at various instants of time. The magnitude of DOM at the mid gap has same value at $t = 0, 5, 10$ and varies periodically with fractional change in time period (Figure 7.5b). Periodic swings are also observed at both left and right edges.

Now, we have studied the effect of polarized EM wave on this structure. The bandgap and the edges of DOM are shifted toward higher frequencies with increase in the angle of incidence in the case of p -polarized EM wave as shown in Figure 7.6. The maximum shift

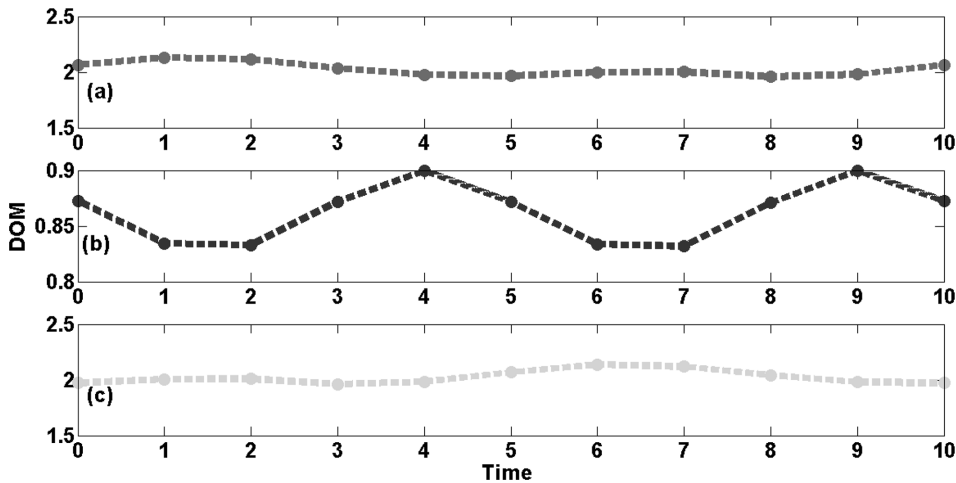


FIGURE 7.5

The variation of DOM at the (a) left edge, (b) mid gap, and (c) right edge at different instants of time.

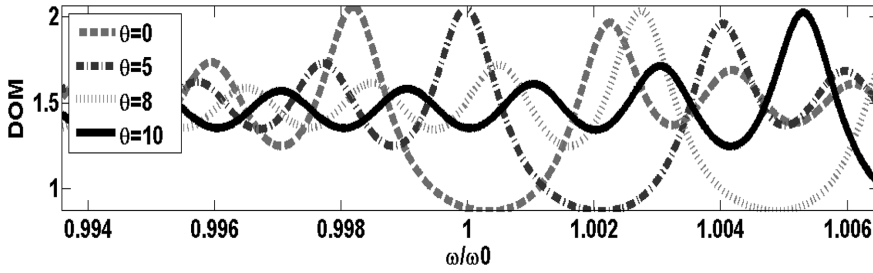


FIGURE 7.6

The variation of DOM with different incident angles in the case of p -polarized wave.

is dominated by the incident angle. At 10° incident angle, the bandgap almost disappears as it is shifted toward the higher frequency, which does not lie in our selected frequency range (solid black line). The magnitudes of the DOM at both edges as shown in Figure 7.7a and c have been decreased, while in the mid gap (Figure 7.7b), it has been increased with increase in the angle of incidence.

Also, for s -polarized EM wave, the bandgap and edges of DOM are shifted toward the higher frequencies with increase in the angle of incidence as shown in Figure 7.8. The greater is the angle of incidence, the greater is the shift. The magnitude of DOM has increased at both the edges as shown in Figure 7.9a and c with increase in incident angle. However, it is decreased at mid gap as shown in Figure 7.9b, which is contrary to the p -polarized wave shown in Figure 7.7b. From the above results, we have found that DOM get modified and dynamically tuned with the AO effect.

We have further extended our study by considering one of the layers of PC to be doped with the active gain material. For this, we consider layer B (see Figure 7.1), which is high index layer and assume that it is doped with an active material having a linear gain per unit length of g .

A photon percolating along the lattice from left to right would actually make many passes through each gain region before its center of energy moves off to the right at a velocity v_g . The effective gain may be qualitatively estimated by assuming that the small

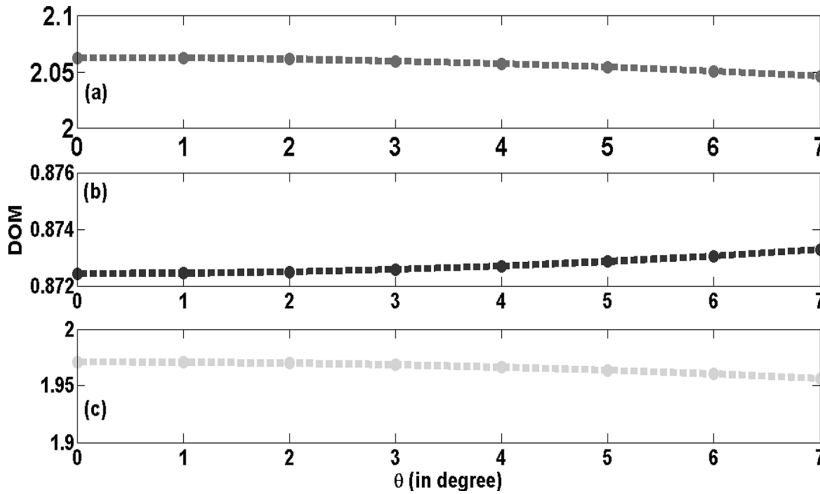


FIGURE 7.7

The variation of DOM with incident angle at (a) left edge, (b) mid gap, and (c) right edge for p -polarized wave.

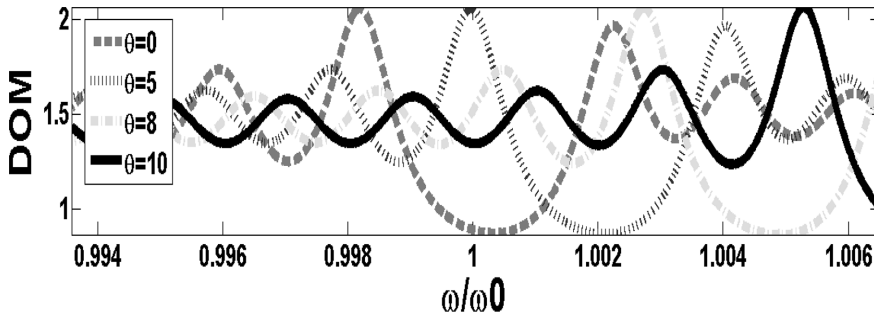


FIGURE 7.8

The variation of DOM with different incident angles in the case of s-polarized wave.

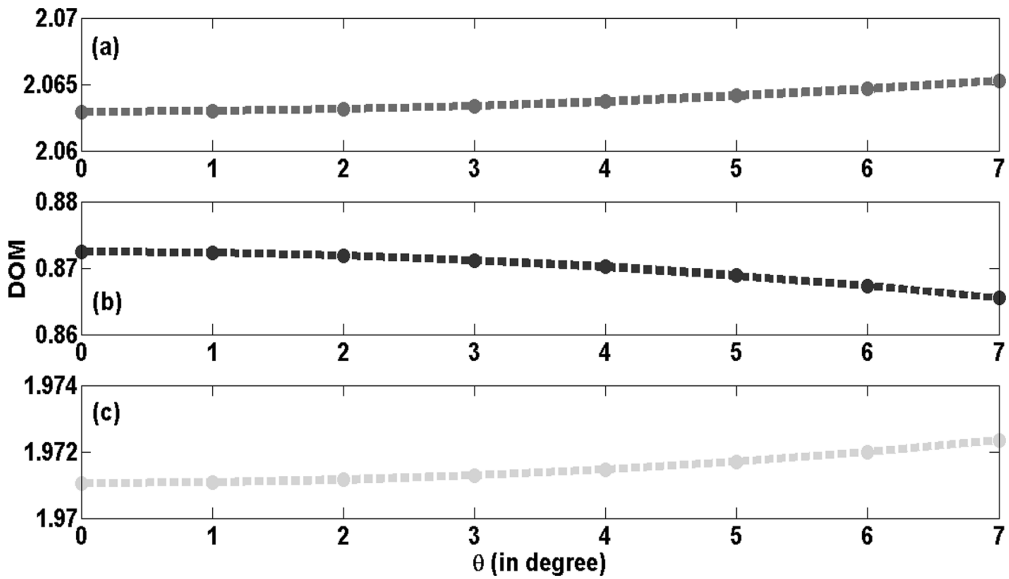
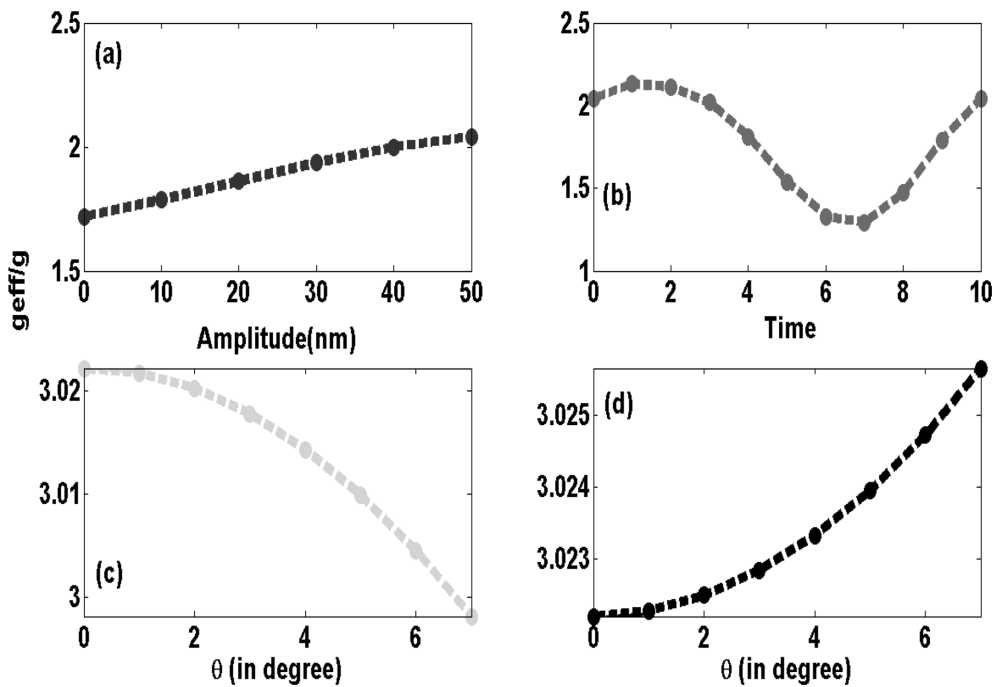


FIGURE 7.9

The variation of DOM with incident angle at (a) left edge, (b) mid gap, and (c) right edge in the case of s-polarized wave.

value of v_g , which is entirely due to an increased optical path length l_{eff} that is larger than the expected value $l = d_B/n_B$. We have chosen $g_{eff}/g \equiv l_{eff}/l = cn_B/v_g$ as $\rho = 1/v_g$, we have $g_{eff}/g \equiv l_{eff}/l = \rho n_B$ (Acklin et al. 1993). With an increase in the acoustic amplitude, layer B gets compressed, due to which it becomes denser giving rise to a larger refractive index value n_B , which indeed increases l_{eff} . It is found that the effective gain is modified by changing the amplitude and time period of the acoustic wave as well as the incident angle of the EM in 1D PC. Figure 7.10 shows the variation of g_{eff}/g as a function of amplitude, time period of acoustic wave, and incident angle of EM wave. From Figure 7.10, it can be seen that the effective gain has been decreased with the incident angle in the case of p-wave. Therefore, it is not desirable to build band edge laser for p-polarized EM wave.

**FIGURE 7.10**

The calculated ratio g_{eff}/g as a function of (a) the acoustic amplitude, (b) the fraction of acoustic time period, (c) theta for *p*-wave, and (d) theta for *s*-wave.

7.5 Conclusions

In summary, we have tailored the EM DOM in a PC, whose refractive indices and periodicity have been perturbed by an acoustic wave. It has been found that, for a particular angular frequency (1.214×10^{15} rad/s) near the left edge of PBG, the DOM is increased with increase in acoustic amplitude. Also, with a fractional change in the time period of the acoustic wave, the PBG and the magnitude of DOM show periodic swing from the central frequency, dominated by acoustic amplitude. An interesting result has been seen in case of *p*-wave and *s*-wave. The PBG and DOM are shifted toward higher frequencies for *p*-wave and for *s*-wave. The effective gain is strongly modified with acoustic amplitude, time period of acoustic wave, and polarization of EM wave. As band-edge laser work at some particular frequency, the results of this chapter will be useful in making band-edge laser.

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Embedded Liquid Crystal Defect with Graphene Layers in Asymmetric One-Dimensional Photonic Crystal as Sensor Application

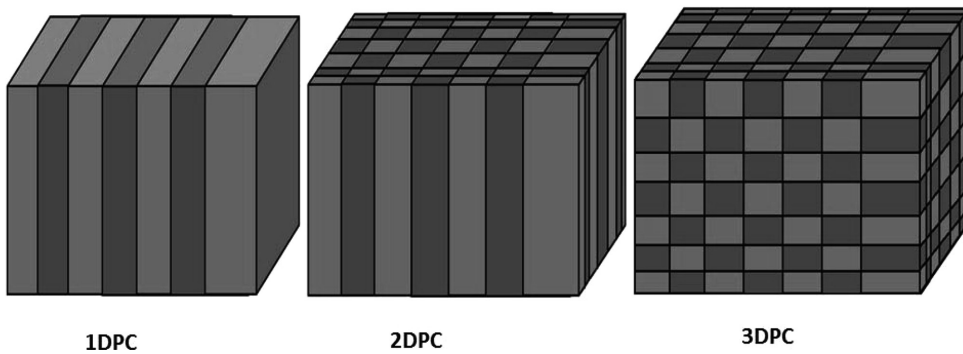
Pawan Singh, Krishan Pal, Khem B. Thapa, Narinder Kumar, and Devesh Kumar

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8.1 Introduction

Photonic crystals (PCs) have been of great interest in the past decades to investigate, which is due to photonic bandgaps (PBGs) that have special property to obstruct the transmission of electromagnetic wave. Reyleigh (1887) investigated that the control of electromagnetic wave is inside the periodic structure. Bykov (1972) suggested that the periodic structure can be used to control the spontaneous emission. John (1987) and Yablonovitch (1987) successfully suggested that the possibility of spontaneous emission management and propagation of radiation can be controlled using a periodic structure of the dielectric materials. Many research papers have published in the field of PCs and its technology in addition to the above-mentioned articles. Basically, PCs are the media in which dielectric materials are arranged periodically with regulation or modulation of the refractive indices in periodic structures. Such periodic arrangements of the dielectric materials have some special properties that can be used in different areas such as photonics, optoelectronic, nanoscience, and nanotechnology.

**FIGURE 8.1**

Schematic of photonic crystals (PCs): one-dimensional photonic crystal (1D PC), two-dimensional photonic crystal (2D PC), and three-dimensional photonic crystal (3D PC). (From Joannopoulos, J.D. et. al., *Photonic Crystals: Molding the Flow of Electromagnetic Wave*, Princeton Univ. Press, Princeton, NJ, 1995.)

PCs can be categorized into one dimensional (1D), two dimensional (2D), and three dimensional as shown in [Figure 8.1](#). 1D PCs are periodic structure of dielectric materials in which the modulation of dielectric permittivity in only one direction is considered, which are very easy to fabricate. Its optical properties can be investigated using transfer matrix method (TMM), which can be satisfied with experiments. The optical properties of 2D PCs can be investigated using plane wave expansion (PWE) method, beam propagation method (BPM), finite element method (FEM), and finite difference time domain (FDTD) method, usually used in waveguides.

In 1D PCs, there is the regulation of dielectric permittivity in only one direction while the other two directions are uniform. Such 1D PCs can be used in the fabrication of anti-reflection coating on the surface of optical devices such as prisms and lenses. 2D PCs can be found in the nature, for example, the wings of butterfly, which have 2D periodic lattice that is responsible for the reflection of light while the third direction is uniform. In 3D PCs, dielectric permittivity varies in all three dimensions, and the number of possible configuration of 3D PCs is larger than 1D and 2D PCs.

When the electromagnetic wave propagates in a crystal, there exists a frequency range, which is not allowed to propagate inside the PCs; such range of frequency is called PBG (King and Wu 2015; Srivastava et al. 2008; Thapa et al. 2006). Such property of the PBG plays a special role in manipulating the light for optical devices. PBG materials can be used in the fabrication of low-loss mirrors, omnidirectional reflectors, antenna arrays, optical fiber communications, and controlled emission devices. The frequency range of PBG region of a periodic structure of the dielectric materials is analogous to the frequency range of electronic bandgap (EBG) of periodic potential electronic eigenstates in the crystal.

The defect of a crystal structure has strongly localized electron states in between the EBG region, for instance, when an intrinsic crystal is made of an extrinsic crystal by adding some impurities, for example, p- and n-type semiconductor. Similarly, if we insert defect layer in the PCs, we obtain mid-gap defect mode whose eigenfunctions are strongly localized, called as localized defect modes. Defect mode PBG can be used in the fabrication of multichannel filters, single wavelength transmissions, tunable devices, reflectors, broadband applications, and so on.

Artificial opals can be fabricated by self-colloidal particle process, which is simple and cost effective, and the fabricated opal has 3D periodic structures. Holographic lithography, a step-down process, is also used to fabricate 2D and 3D uniform PCs. Electron beam

lithography can be used in the fabrication of photonic device, which is based on the pattern of the different dielectrics. By combination of state-of-the-art lithography with electrochemical etching process, 2D low imperfection PC can be fabricated (Joannopoulos et al. 1995; Sakoda 2005; Skorobogatiy and Yang 2009; Sukhoivanov and Guryev 2009). In the case of 3D PCs, the planar lithographical technique is used with a multistep process technique. 1D PCs can be fabricated using a thin-film technology, in which thin films are fabricated on the surface of each fabricated dielectric layer. The applications of PC depend on the existence of the PBG region. PCs are used in many device applications such as optoelectronic devices, tunable optical devices, optical filters, low-loss mirrors, splitters, wave harmonic devices, switching devices, and sensors.

Liquid crystal (LC) is an electro-optic material, and the optical property of the LCs changes due to the orientation of molecules. 2D material, graphene, has excellent electronic and optical properties as well and is used in many optical devices to enhance the optical properties of the devices. In this chapter, we study the optical properties of asymmetric 1D PC with LC defect, where LC is embedded with graphene layers by considering the orientation of LC molecules under the influence of the electromagnetic wave. The graphene layer is stuck to one end of the asymmetric finite 1D PC, and the graphene layer asymmetric 1D PC is an embedded LC as the defect. Prior to this, we also discuss the optical constant of the nematic liquid crystal (NLC) and graphene, and then the transmittance of the graphene layer asymmetric 1D PC with defect LC is analyzed. The absorption peaks of the considered structure analyze for a sensor application due to metallic behavior of the graphene.

8.2 Theory and Methodology

8.2.1 Theory of Band Formation in PC

We consider the propagation of electric field in the z -direction inside the PC, which is formed by a binary dielectric material as shown in Figure 8.2. Using the Maxwell's equations for nonmagnetic materials, the wave equation for the electric field $E_x(z, t)$ is given by the following (Sakoda 2005):

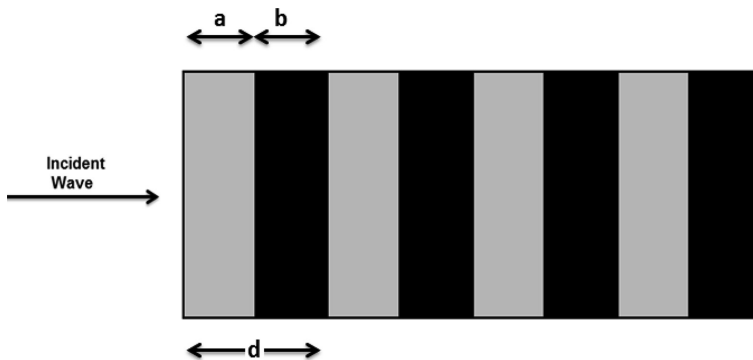


FIGURE 8.2

Schematic of one-dimensional photonic crystal of the binary dielectric materials having periodicity $d = a + b$. (From Sakoda, K., *Optical Properties of Photonic Crystals*, Springer, New York, 2005.)

$$\frac{1}{\varepsilon(z)} \frac{\partial^2 E_x(z)}{\partial z^2} = \frac{1}{c^2} \frac{\partial^2 E_x(z)}{\partial t^2}, \quad (8.1)$$

where $\varepsilon(z)$ is dielectric function that depends on the position z and $\varepsilon(z)$ is also called the relative dielectric constant of each layer inside 1D PC. The dielectric function is periodic dependent on the position z . According to the Bloch theorem for the periodicity $d = a + b$ of the binary dielectric materials as shown in [Figure 8.2](#),

$$\varepsilon(z + d) = \varepsilon(z). \quad (8.2)$$

As $\varepsilon(z)$ is a periodic function, then its inverse is also a periodic function, which can be expanded with the help of the Fourier series as given as follows:

$$\varepsilon^{-1}(z) = \sum_{n=-\infty}^{\infty} C_n \exp\left(\frac{2i\pi n z}{d}\right), \quad (8.3)$$

where $\{C_n\}$ are Fourier constants and n is an integer.

On considering $n = 0, +1$, and -1 values, the inverted dielectric function is expanded into three terms with C_0, C_{-1} , and C_1 coefficients.

$$\varepsilon^{-1}(x) \approx C_0 + C_1 \exp\left(\frac{2i\pi z}{d}\right) + C_{-1} \exp\left(-\frac{2i\pi z}{d}\right) \quad (8.4)$$

The electric field inside the crystal, complex in nature, is defined by the following:

$$E_k(z, t) = u_k(z) \exp\{i(kz - \omega_k t)\}, \quad (8.5)$$

where $u_k(x)$ is a periodic function and ω_k is the angular frequency:

$$u_k(z + d) = u_k(z). \quad (8.6)$$

Hence $E_k(x, t)$ can be expanded using Fourier series:

$$E_k(z, t) = \sum_{n=-\infty}^{\infty} E_n \exp\left\{i\left(k + \frac{2\pi n}{d}\right)z + i\omega_k t\right\}. \quad (8.7)$$

Putting Equations (8.4) and (8.7) into Equation (8.1), we get

$$C_1 \left\{k + \frac{2\pi(n-1)}{d}\right\}^2 E_{n-1} + C_{-1} \left\{k + \frac{2\pi(n+1)}{d}\right\}^2 E_{n+1} \approx \left\{\frac{\omega_k^2}{c^2} - C_0 \left(k + \frac{2\pi n}{d}\right)^2\right\} E_n. \quad (8.8)$$

For

$$n = -1, E_{-1} \approx \frac{c^2}{\omega_k^2 - C_0(k - 2\pi/d)^2 c^2} \left\{C_1 \left(k - \frac{4\pi}{d}\right)^2 E_{-2} + C_{-1} k^2 E_0\right\} \quad (8.9)$$

For

$$n=0, E_0 \approx \frac{c^2}{\omega_k^2 - C_0 k^2 c^2} \left\{ C_1 \left(k - \frac{2\pi}{d} \right)^2 E_{-1} + C_{-1} \left(k + \frac{2\pi}{d} \right)^2 E_1 \right\}. \quad (8.10)$$

We can find the coupled wave equations if we neglect the other terms in both Equations (8.9) and (8.10) and obtain the following Equations (8.11) and (8.12):

$$(\omega_k^2 - C_0 k^2 c^2) E_0 - C_1 \left(k - \frac{2\pi}{d} \right)^2 c^2 E_{-1} = 0, \quad (8.11)$$

$$-C_{-1} k^2 c^2 E_0 + \left\{ \omega_k^2 - C_0 \left(k - \frac{2\pi}{d} \right)^2 c^2 \right\} E_{-1} = 0, \quad (8.12)$$

For the nontrivial solution of Equations (8.11) and (8.12), the determinant of matrix should be disappeared:

$$\begin{vmatrix} \omega_k^2 - C_0 k^2 c^2 & -C_1 \left(k - \frac{2\pi}{d} \right)^2 c^2 \\ -C_{-1} k^2 c^2 & \omega_k^2 - C_0 \left(k - \frac{2\pi}{d} \right)^2 c^2 \end{vmatrix} = 0,$$

If we consider $g = k - \pi/d$, the solution can be written as follows:

$$\omega_{\pm} \approx \frac{c\pi \sqrt{C_0 \pm |C_1|}}{d} \pm \frac{cdg^2}{|C_1|\pi} \left(C_0 - \frac{|C_1|^2}{2} \right).$$

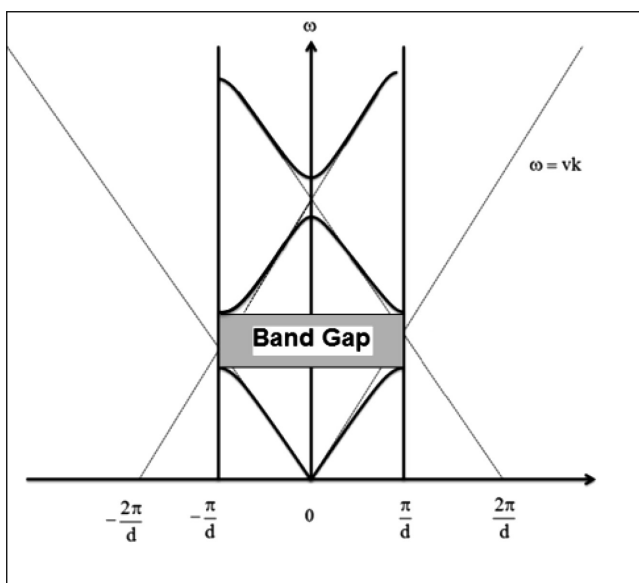
The dispersion relation, photonic band structure, is shown in [Figure 8.3](#). If $|g| \ll \pi/d$, then there exists no bandgap in this interval: $\frac{c\pi}{d} \sqrt{C_0 - |C_1|} < \omega < \frac{c\pi}{d} \sqrt{C_0 + |C_1|}$

If $C_1 = 0$, then the gap vanishes. In the presence of periodic modulation of dielectric constant, the modes related to $k \approx \pi/d$ and $k \approx -\pi/d$ are mixed with each other, which lead to the splitting of frequency. Due to the presence of periodic modulation, the wave vectors, which are only difference by $2\pi/d$, should be considered the same.

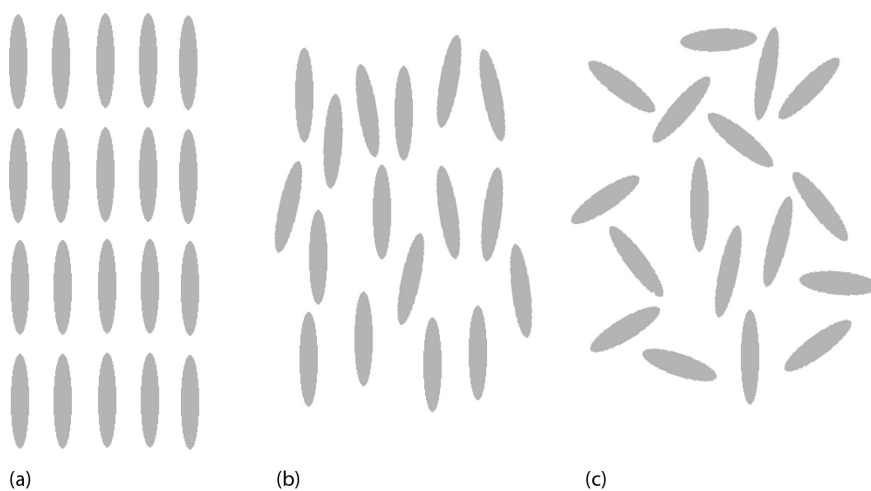
8.2.2 Liquid Crystal

LCs have intermediate-phase between liquid and crystal because they have both liquid-like flow property and crystal-like crystalline property, that is, order and periodicity as shown in [Figure 8.4](#). They are excellent materials that have nonlinear optical properties, which is applicable in many photonic devices.

It is well known that LCs are mesogens and produce novel optical properties due to direction-dependent molecular properties. LCs can be characterized into three types: thermotropics, polymeric, and lyotropics. LCs have temperature, concentration, substituents, and so on, depend on optical properties. The LC exists in different phases that are called

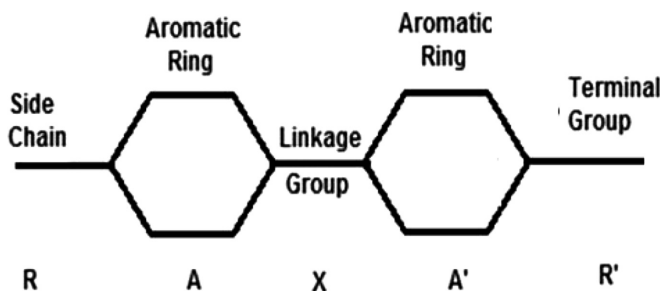
**FIGURE 8.3**

Solid lines represent dispersion relation for 1D PC; dashed lines represent the dispersion lines for uniform materials, when the dispersion lines cross each other; they repeal each other and form bandgap; the boundary for the first Brillouin zone is given by two vertical lines. (From Sakoda, K., *Optical Properties of Photonic Crystals*, Springer, New York, 2005.)

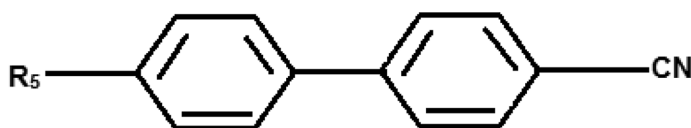
**FIGURE 8.4**

A molecular representation of (a) crystalline phase, (b) liquid crystal phase, and (c) liquid phase.

nematic, cholesteric, smectic, and ferroelectric. Basically, LCs are aromatic, and they contain benzene rings in the structure. Therefore, the LCs are generally known as benzene derivatives. The general structure of organic LC is shown in Figure 8.5; it consists of a side chain (R), two and more benzene rings (A, A') connected by a linkage group (X) at the other end, a terminal group (R') is connected (Chandrasekhar 1992; Khoo 2007).


FIGURE 8.5

General molecular structure of liquid crystal (LC). (From Khoo, I.C., *Liquid Crystals*, Wiley Interscience, New Jersey, 2007.)


FIGURE 8.6

Molecular structure of 5CB liquid crystal. (From Khoo, I.C., *Liquid Crystals*, Wiley Interscience, New Jersey, 2007.)

In this study, we consider 5CB LC, where $R = R_5$ and $R' = \text{CN}$, which is shown in Figure 8.6. So, dielectric constants, electronic constants, transmission spectra, absorption spectra, optical nonlinearity, anisotropy, and more other properties depend on the method of synthesis of these molecules.

Besides this, the order parameter is an important parameter that characterizes the phase of the LC. The order parameter for the perfect crystalline state is 1, and the purely liquid phase is 0. It means that the order meter for LC should belong to the regions $0 < S < 1$. The order parameter depends on the angle made by molecular axis with the director axis. The order parameter (S) can be defined as follows:

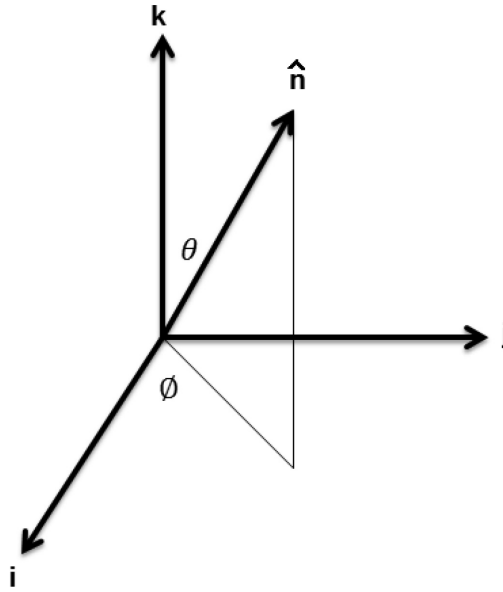
$$S = \frac{1}{2} \langle 3 \cos^2 \theta - 1 \rangle. \quad (8.13)$$

The $\langle \rangle$ brackets represent the average of the quantity over the whole ensemble. If there is presence of asymmetric dopants or intermolecular interactions, a general tensor form of order parameter (S_{ij}) is defined as follows:

$$S_{ij} = \frac{1}{2} \langle 3(\hat{n} \cdot \hat{i})(\hat{n} \cdot \hat{j}) - 1 \rangle, \quad (8.14)$$

where i, j , and k are unit vectors along the molecular axes. Three order parameter diagonal components are given below with reference to Figure (8.7):

$$S_{ii} = \frac{1}{2} \langle 3 \sin^2 \theta \cos^2 \phi - 1 \rangle \quad (8.15)$$

**FIGURE 8.7**

Representation of a liquid crystal director vector in three dimensions along three axes x , y , and z with i , j , and k unit vectors. (From Khoo, I.C., *Liquid Crystals*, Wiley Interscience, New Jersey, 2007.)

$$S_{jj} = \frac{1}{2} \langle 3 \sin^2 \theta \sin^2 \phi - 1 \rangle \quad (8.16)$$

$$S_{kk} = \frac{1}{2} \langle 3 \cos^2 \theta - 1 \rangle, \quad (8.17)$$

where $S_{ii} + S_{jj} + S_{kk} = 0$, it is a traceless tensor.

The dielectric permittivity of LCs is in the tensor form that can be represented in 3×3 matrix:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}, \quad (8.18)$$

where ε depends on the components that depend on the molecular axis dielectric permittivity components ε_{ij} , where $i, j = x, y$, and z . For isotropic phase, dielectric permittivity is converted to diagonal matrix, off-diagonal elements are zeros, and $\varepsilon_{\perp}, \varepsilon_{\parallel}$ are ordinary and extraordinary dielectric constants of the LC.

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{\perp} & 0 & 0 \\ 0 & \varepsilon_{\perp} & 0 \\ 0 & 0 & \varepsilon_{\parallel} \end{bmatrix} \quad (8.19)$$

The average refractive index of LC is dependent on the ordinary and extraordinary refractive indices, that is, n_o and n_e of the LC can be given by Equation (8.20). The average refractive index is used to study the bulk form of LC, that is,

$$n_{avg} = \frac{2n_o + n_e}{3} \quad (8.20)$$

LCs are very interesting materials that have nonlinear optical properties. The use of LC as defect is the periodic structure that helps to achieve tunable optical properties. The dielectric permittivity of LC is temperature and electric field dependent, so the periodic structure infiltrated with the LC gives the tunable defect mode and tunable PBG. Such periodic structure with defect of LC can be used as bi-stable switches, diode operation, feedback laser, metamaterials, solar cell, LCD, and so on.

LCs are anisotropic and highly birefringent materials, which have unusual properties. We use nonlinear devices to achieve nonlinear and tunable properties. LCs have dielectric tensor that depends on the directions of the LC molecules, which means that the dielectric constant of the LC is changed according to the molecular orientation. The direction-dependent properties of LC make it to use in the nonlinear and tunable device fabrication.

8.2.2.1 Free Energy of the NLC

If we apply the external field on the NLC cell, the molecules undergo deformation related to its director axis. There are three possible deformations of the LC director axis: twist, splay, and bend with their defined Frank elastic constants K_1 , K_2 , and K_3 . The theoretical details on the free energy densities related to liquid crystals deformations was given by Frank. (Chandrasekhar 1992; Khoo 2007). These deformations are related to the change in the $n(r)$, and the deformation energies depend on the spatial derivatives of the $n(r)$. The deformation energies corresponding to the deformation are given by the following:

$$\text{Splay: } f_1 = \frac{1}{2} K_1 (\nabla \cdot n)^2 \quad (8.21)$$

$$\text{Twist: } f_2 = \frac{1}{2} K_2 (n \cdot \nabla \times n)^2 \quad (8.22)$$

$$\text{Bend: } f_3 = \frac{1}{2} K_3 (n \times \nabla \times n)^2, \quad (8.23)$$

where K_1 , K_2 , and K_3 are the Frank elastic constants related to their deformations such as splay, twist, and bend.

On application of the external electric field on the LCs, more than one deformation is induced in the cell. If all the possible deformations are induced in the cell, then the free energy can be written as follows:

$$F_d = \frac{1}{2} K_1 (\nabla n)^2 + \frac{1}{2} K_2 (n \nabla \times n)^2 + \frac{1}{2} K_3 (n \times \nabla \times n)^2 \quad (8.24)$$

If we take one elastic constant approximation $K_1 = K_2 = K_3 = K$, then the free energy can be written as follows:

$$F_d = \frac{1}{2} K [(\nabla n)^2 + (\nabla \times n)^2] \quad (8.25)$$

Equation (8.25) describes the director axis deformation in the bulk NLC; such approximation affects the characteristics of the LC in very small manner, which can be neglected. Due to the presence of nonlinearity, LCs can be used in many tunable optical devices (Figure 8.8).

Busch and John (1999) suggested that the inverse opal coated with the LC can be used to tune the bandgap. The refractive index of the LC has temperature and electric field dependent, which helps to tune the bandgap of the periodic structure of the dielectric materials. Another method used to achieve the tunable bandgap is infiltration of LC in the pores and creates the LC defects in 1D PC. The tunable optical properties of such periodic structure depend on the properties of the LCs. Therefore, LC has nonlinear optical properties that help to gain all the optical properties, that is, all optical controls of electromagnetic wave in periodic structures to achieve the tunability of the bandgap spectra (Entezar et al. 2013; Graubard et al. 2005; Kang et al. 2001; Leonard et al. 2000; Mingaleev et al. 2004; Miroshnichenko et al. 2006; Mohamed et al. 2016; Ozaki et al. 2005; Schuller et al. 2003; Yoshino et al. 1999). LC has been revolution materials in the field of display applications. LC has unique properties for display, which reduces the size of the display device and consuming less power for display. LC is a sandwich between the glass plates for ambient light display illumination, which is found in various phases; chiral nematic phase has its special use in the thermometer. Chiral NLC reflects the specific colored light on the basis of the temperature and analyzes the color of the thermometer, which is possible to analyze the accurate gauge temperature. LC temperature sensor can also be used to check the connections on the circuit boards. LCs are very important material, and various types of LCs have been discovered. LC is a significant material in the field of optical imaging and recording. LC is a sandwich between the photoconductors; when the light falls on the photoconductor, the conductivity of the photoconductors

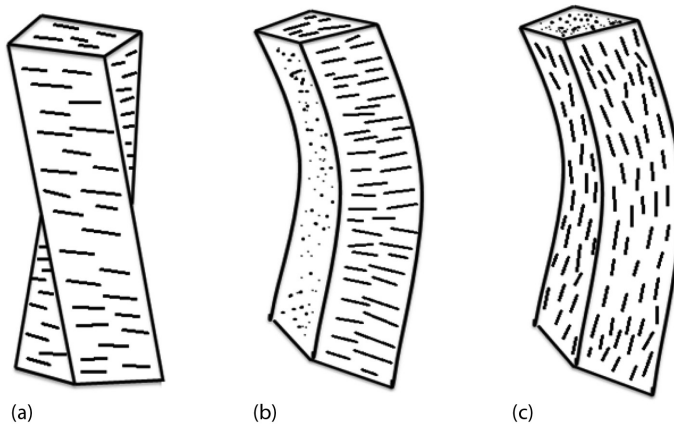


FIGURE 8.8

All three possible deformations of liquid crystal: (a) Twist, (b) splay, and (c) bend. (From Khoo, I.C., *Liquid Crystals*, Wiley Interscience, New Jersey, 2007.)

is increased and an electric field is induced based on the light intensity of the LC cell. By transmitting the electric pattern by electrode, image can be recorded. Besides this, LC can be used in a nanostructured PC and optical waveguides for making simply tuned attenuators, polarization controllers, equalizers, image transmitting fibers, phase simulators, and so on. Moreover, LC can also be used in the sensing applications such as chemical sensing, gas sensing, and biological sensing and in the fiber optic sensors. They can also be used in the PC to make tunable optical devices such as optical filters, switches, splitters, mirrors, and lasing devices. For such optical devices, the LC cell is a sandwich between the periodic layers of dielectric materials. The electromagnetic wave made to fall on the periodic structure, when the intensity of light is equal to or greater than the threshold intensity of LC molecules, orients and transmits the light wave according to the orientation. Such periodic structure gave the tunable bandgap with defect peaks in the PBG regions. LCs find their application in the solar cell device, a very special type of discotic LC helps to fabricate the efficient organic photovoltaic solar cell. The utilization of self-organization of discotic LC and crystalline organic materials for charge transport is the main factor to fabricate such type of solar cell. LC is very inexpensive to get clean and green energy.

8.2.3 Graphene

The innovation of graphene generates to new division in the field of nanoscience and nanotechnology (Novoselov et al. 2004). Graphene is the first 2D nanostructured and conducting material, which reduces the size of the electronic devices by its specific electronic and optical properties (Geim and Novoselov 2007). A single graphene layer is deposition of sp^2 carbon atoms in a hexagonal lattice similar to honeycomb. Graphene is the fundamental element of the allotropes of carbons: graphite, carbon nanotubes (CNTs), fullerenes (C_{60}), and so on. Graphene has a very high mobility of its charge carriers at room temperature so it can be used in electronic devices for several applications.

It is a very important material in the field of photonics and optoelectronics. Graphenes have unusual electronic and optical properties for the device fabrication. It has no bandgap and semi-metallic nature. Berman and Kezerashvili (2011) investigated frequency-dependent band structure of the graphene-based 1D PC formed by the arrangement of periodically alternating graphene and dielectrics, which is embedded in the background dielectric media. Graphene is also important to make photonic modulators, which is theoretically investigated by Gosciniak and Tan (2013), a study showed that a 3 dB modulation is possible in 600 nm waveguide with energy per bit below 1 fJ/bit. The 1D graphene-dielectric periodic structure plays a major role in bandgap engineering, polarization splitters, tunable devices, stop filters, potential applications, high gain antenna, force generator in terahertz band, and so on.

The optical properties of graphene-containing periodic structure can be tuned by gate voltage of the graphene. Tunable magneto-optical effect produced by graphene-based PCs with the enhancement of interactions between light and matter thus enhanced absorption properties. The modification in the conductivity and dielectric permittivity can be done by changing the chemical potential of the graphene. Due to its absorption property, graphene is a significant material to investigate the sensing phenomena, which produce by graphene-embedded LC periodic system. Hexagonal lattice is found in the graphene, so its electronic wave functions from different atoms are overlaps such as $p_z(\pi)$ with s or p_x and p_y is zero due to the presence of symmetry. The p_z electrons can be considered independent of other valence electrons, and pi-bonds are formed in the structure due to p_z electrons.

On considering first nearest-neighbor interactions only, the electronic spectrum of total Hamiltonian can be described with the help of pi-band approximation and obtains the dispersion relations (Bonaccorso et al. 2010):

$$E^{\pm}(k_x, k_y) = \pm \gamma_0 \sqrt{1 + 4 \cos \frac{\sqrt{3} k_x a}{2} \cos \frac{k_y a}{2} + 4 \cos^2 \frac{k_y a}{2}}, \quad (8.26)$$

where $a = \sqrt{3}a_{cc}$ and γ_0 is the transfer integral between the first neighbor π -orbitals and a_{cc} is the distance between carbon and carbon atom.

In $\pi - \pi^*$ model with considering one p_z electron per atom, the negative energy branch is fully occupied, whereas the positive branch is empty. These two bands touch at K points. If the Fermi surface is defined by the K and K', then π - and π^* -bands arise.

$$E^{\pm}(\kappa) = \pm \hbar v_F |\kappa|, \quad (8.27)$$

where $\kappa = k - K$, and v_F is the electronic group velocity with a value of 10^6 ms^{-1} .

Equation (8.27) is the solution of the effective Hamiltonian at the point $K(K')$, $H = \pm \hbar v_F (\sigma \kappa)$, where $\kappa = -i\nabla$ and σ are the pseudo-spin Pauli matrices. These matrices are operating in the electron amplitude on the graphene sublattices. Graphene has interesting optical properties such as it can be visualized in optical manner and its transmittance property can be introduced in fine-structure constant values. Having no bandgap, graphene is semi-metallic in nature, which limits the application of graphene in the field of electronics. It has a very high leakage current in several applications, which is another reason for its boundation to use in electronic devices. It shows a many transport phenomena such as specific integer and fractional quantum Hall effects, which are properties of 2D Dirac fermions. The minimum conductivity ($4 e^2/h$) of the graphene exists, even when carrier concentration approaches to zero. In graphene, Shubnikov–de Haas oscillation exists with a shift of π due to Berry's phase (Du et al. 2009; Zhang et al. 2005b). Due to the existence of near ballistic transport at room temperature, graphene is an efficient material in the field of nanotechnology such as high-frequency device applications. Broadband application of graphene is also possible due to linear dispersion relation of Dirac cones (Sharma et al. 2007). Although no band arises in the graphene but on the application of electric field on the graphene bilayers or graphene layers in periodic structure, it is possible to achieve bandgap that is tunable based on the gate voltage of the graphene (Al-sheqefi and Belhadj 2015; Fu et al. 2016).

Graphene is a nonlinear material that can be applicable in microwave, terahertz, and optoelectronic applications, optical sensing applications, nonlinear photonic device applications, lasing action application, transparent conducting window, photoactive material, channel for transport of charge and catalytic action, light-emitting devices, photodetectors, smart window, bi-stable display, ultrafast lasers, optical limiters, terahertz devices, and optical frequency converters. It is also used in the fabrication of dye-synthesized solar cell in the form of window electrodes (Bae et al. 2010; Wang et al. 2008; Zhang et al. 2005a). It can be synthesized by micromechanical exfoliation of graphene, liquid-phase exfoliation offers scalability, in which graphene nanoribbons are produced, and the width of nanoribbons is less than 10 nm. Chemical vapor deposition, carbon segregation, and chemical methods are also used to synthesize for graphene sheets (Avouris and Dimitrakopoulos 2012; Bonaccorso et al. 2012) (Figure 8.9).

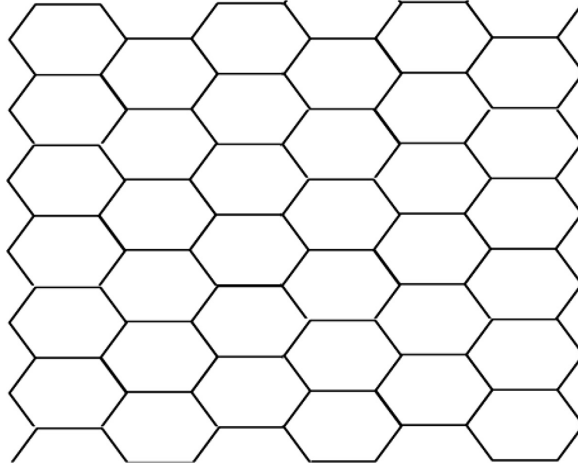


FIGURE 8.9
2D structure of graphene sheet.

The complex dielectric constant of the graphene depends on the gate. The complex optical conductivity of graphene depends on the intraband and interband contributions. The total conductivity of the graphene is given by the following (Bao and Loh 2012):

$$\sigma_{\text{total}} = \sigma_{\text{intra}} + \sigma'_{\text{inter}} + i\sigma''_{\text{inter}}, \quad (8.28)$$

where

$$\sigma_{\text{intra}} = \frac{\sigma_0 4\mu}{\pi \hbar (\tau_1 - i\omega)}; \sigma'_{\text{inter}} = \sigma_0 \left(1 + \frac{1}{\pi} \arctan \left(\frac{\hbar\omega - 2\mu}{\hbar\tau_2} \right) - \frac{1}{\pi} \arctan \left(\frac{\hbar\omega + 2\mu}{\hbar\tau_2} \right) \right),$$

$$\text{and } \sigma''_{\text{inter}} = -\sigma_0 \frac{1}{2\pi} \ln \frac{(2\mu + \hbar\omega)^2 + (\hbar\tau_2)^2}{(2\mu - \hbar\omega)^2 + (\hbar\tau_2)^2}.$$

$$\sigma''_{\text{inter}} = -\sigma_0 \frac{1}{2\pi} \ln \frac{(2\mu + \hbar\omega)^2 + (\hbar\tau_2)^2}{(2\mu - \hbar\omega)^2 + (\hbar\tau_2)^2}$$

Here, $\sigma_0 = e^2 / (4\hbar)$ is a universal optical conductance with the value of $60.8 \mu\text{S}$, using σ_{total} , the calculated dielectric function for graphene sheet is given in Equation (8.29):

$$\varepsilon(\omega) = 1 + \left(\frac{i\sigma(\omega)}{\omega \varepsilon_0 d_g} \right), \quad (8.29)$$

where d_g is the thickness of the graphene layer and ε_0 is the vacuum permittivity.

The complex conductivity of graphene depends on the angular frequency (ω), relaxation time (τ), the chemical potential (μ), and the fixed temperature from Equation (8.28). The dielectric function of graphene sheet is calculated as the function of chemical potential for $\lambda = 1550 \text{ nm}$, temperature (T) = 296 K, and $\tau_1 = 1.2 \text{ ps}$, $\tau_2 = 10 \text{ fs}$ for interband conductivity and intraband conductivity, respectively. The graphene dielectric function has real and imaginary parts, which are responsible for its “metallic nature.”

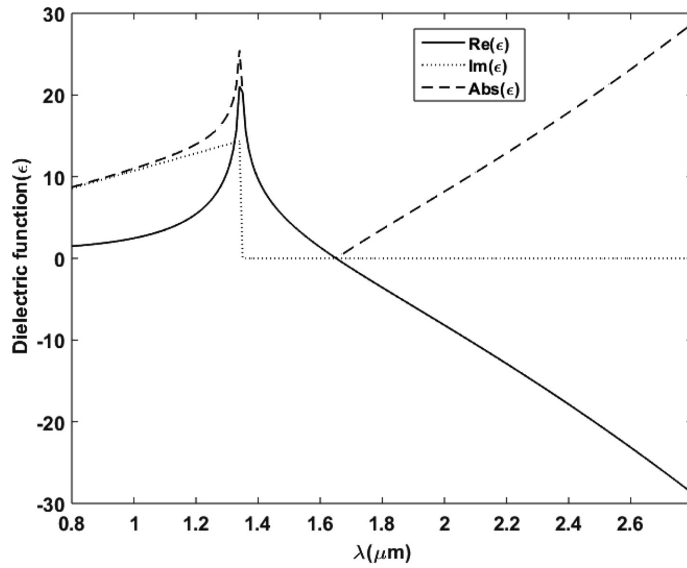


FIGURE 8.10
Behavior of dielectric function of graphene sheet in the microwave region.

Figure 8.10 shows the variation of the dielectric function of graphene versus wavelength at $\mu = 0.4$ eV, where μ is a chemical potential. The dielectric function of graphene has real and imaginary values. Having the imaginary value of the dielectric function, the graphene behaves like metal that is responsible for the absorption effect. Figure 8.10 shows that the real-value dielectric function of graphene first increases and becomes maximum at $\lambda = 1.3 \mu\text{m}$ and then further decreases with increasing wavelength. The imaginary part of the dielectric function first increases and becomes maximum at $\lambda = 1.3 \mu\text{m}$ and then sharply decreases to zero and becomes constant for all further wavelength up to $2.8 \mu\text{m}$. The behavior of dielectric function of graphene has complex, which have real and imaginary values. The real, imaginary, and absolute value of dielectric function have different behaviors in the microwave region.

8.2.4 Optical Behavior of LC Defect 1DPC

To study the effect of orientation of NLC molecules on the transmission property of the periodic structure of Si and glass, $(\text{Si}|\text{Glass})^3|\text{NLC}|(\text{Si}|\text{Glass})^3$, first, we studied the behavior of LC director on the application of electric field. The orientation of LC director depends on the Freedericksz transition value, which is responsible for the different orientations of LC director, which gives us the tunability of defect peak inside the PBG region in the transmission spectra. Second, we discussed the effect of embedded NLC on the graphene layers in the periodic structure. The graphene has interesting optical properties, and we have already discussed the absorption behavior of the graphene layers in the periodic structure of the Si and glass materials with orientation effect of the NLC.

For the study of the optical properties of the periodic structure of Si and glass, $(\text{Si}|\text{Glass})^3|\text{NLC}|(\text{Si}|\text{Glass})^3$, we have used the TMM. We have taken the Si and glass dielectric

materials with refractive indices $n_1 = 3.4$ and $n_2 = 8.5$, respectively. Thicknesses of the dielectric layers are according to the maximum transmission condition given below:

$$n_1 d_1 = n_2 d_2 = \lambda / 4.$$

For the study of the optical properties of the $(\text{Si}|\text{Glass})^3|\text{NLC}|(\text{Si}|\text{Glass})^3$ with the orientation effect of the NLC, we have solved the nonlinear differential equation for NLC, which gives the behavior of LC that help to study the optical properties.

If we consider the plane electromagnetic wave incident on the periodic structure with the defect of NLC, then the LC molecules orient in the particular direction with making an angle ϕ_z . The orientation of the LC molecule depends on the Freedericksz transition intensity of the LC. The director angle $\phi(z)$ of the LC molecule under the interaction of light is analyzed by varying the intensity ratio. The solution of the nonlinear differential equation is dependent on the LC parameters such as intensity ratio of incidence intensity to the Freedericksz threshold intensity and boundary conditions (Kosmidou et al. 2005):

$$\phi_{zz} - \frac{k \sin(2\phi)}{2(1 - k \sin^2 \phi)} \phi_z^2 + \frac{\pi^2 I \sin(2\phi)}{2L^2 I_{fr} (1 - k \sin^2 \phi)(1 - \beta \sin^2 \phi)^{3/2}} = 0(z), \quad (8.30)$$

where ϕ_{zz} and ϕ_z are the double and single partial derivatives of ϕ with respect to z , respectively. k_{33} and k_{11} are bend and splay elastic constants of LC, β is a constant that depends on the ordinary (n_o) and extraordinary (n_e) refractive index of LC, and L is the thickness of LC equal to 100 nm. The k and β are given by the following (Stephen and Straley 1974) (Figure 8.11):

$$k = \frac{k_{33} - k_{11}}{k_{33}}, \beta = 1 - \left(\frac{n_o^2}{n_e^2} \right).$$

Freedericksz threshold intensity, that is, I_{fr} , can be calculated by the following:

$$I_{fr} = \frac{ck_{33}\pi^2}{n_o\beta L^2}, \text{ where } c = 3 \times 10^8 \text{ m/s}.$$

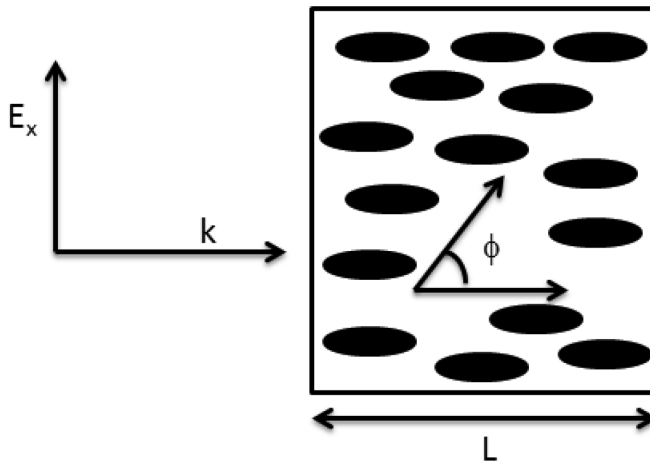


FIGURE 8.11

Schematic of molecule director angle under the external electric field.

We apply the Dirichlet-type boundary conditions (BCs) to solve the Equation (8.30), which shows the director behavior of LCs (Ong 1983; Polycarpou et al. 2012; Zel'dovich et al. 1981):

$$\phi(z=0)=0 \text{ and } \phi(z=L)=0 \quad (8.31)$$

Equation (8.31) is considered for firm anchoring of LCs, which help in the solution of Equation (8.30). With above BCs, first, we multiply Equation (8.30) by $2\phi_z$, then integrate with respect to z , and then determine the integration constant in terms of maximum director angle $\phi_{\max}$. On further solving, we get Equation (8.32) as follows:

$$\left(\frac{d\phi}{dz}\right)^2 = \frac{4A}{\beta} \left[\frac{1}{(1-\beta \sin^2 \phi_{\max})^{1/2}} - \frac{1}{(1-\beta \sin^2 \phi)^{1/2}} \right], \quad (8.32)$$

where $A = \frac{\pi^2 I}{2L^2 I_{fr}}$ with respect to the maximum director angle $\phi_{\max}$, which reaches maximum at the middle of the cell at $z = L/2$. For such condition, we have

$$\int_0^{\phi_{\max}} \frac{d\phi}{(\sin^2 \phi_{\max} - \sin^2 \phi)} = \frac{L}{2} (2A)^{1/2}. \quad (8.33)$$

On integrating Equation (8.33), we can find the exact solution. For any thorough solution, we conclude that there is no change in molecular orientation when $I < I_{fr}$, and molecules get reorientation when $I > I_{fr}$ and reach a maximum value of $\phi_{\max}$ at the middle of the cell. To find out the solution of Equation (8.30), we consider the second-order terms in calculations for when the intensity ratio of (I/I_{fr}) increases, but when the ratio decreases, we also take count of the high-order degree terms such as the fourth order in the calculations. The orientation/re-orientation of the LC molecules are dependent on the intensity of electromagnetic wave (I), which is equal to or greater than the Freedericksz transition intensity (Blinov et al. 2011; Khoo 1981).

8.3 Results and Discussion

To understand the effect of the orientation of LC molecules and the metallic nature of the graphene, we have studied the optical properties of the periodic structure with and without the defect. We have calculated the bandgap and transmittance of the 1D PC of the Si and glass materials. The bandgap represents the forbidden gap region due to periodicity of the dielectric materials, which is generalized by the Bloch's theorem for the periodic dielectric materials. Such bandgap is equivalent to the 100% reflectance and 0% transmittance of the 1D PC of the Si and glass materials.

Figure 8.12 shows the simple PBG and transmission/reflection spectra of 1D PC structure of Si and glass materials, (Si|Glass)⁶, with the wavelength of the propagation wave is 1.5 μm . The thicknesses and refractive indices of the Si and glass dielectric materials are 110 and 250 nm and 3.4 and 1.5, respectively. The PBG region is obtained for 1.20 μm to 2.06 μm and PBG is 0.86 μm .

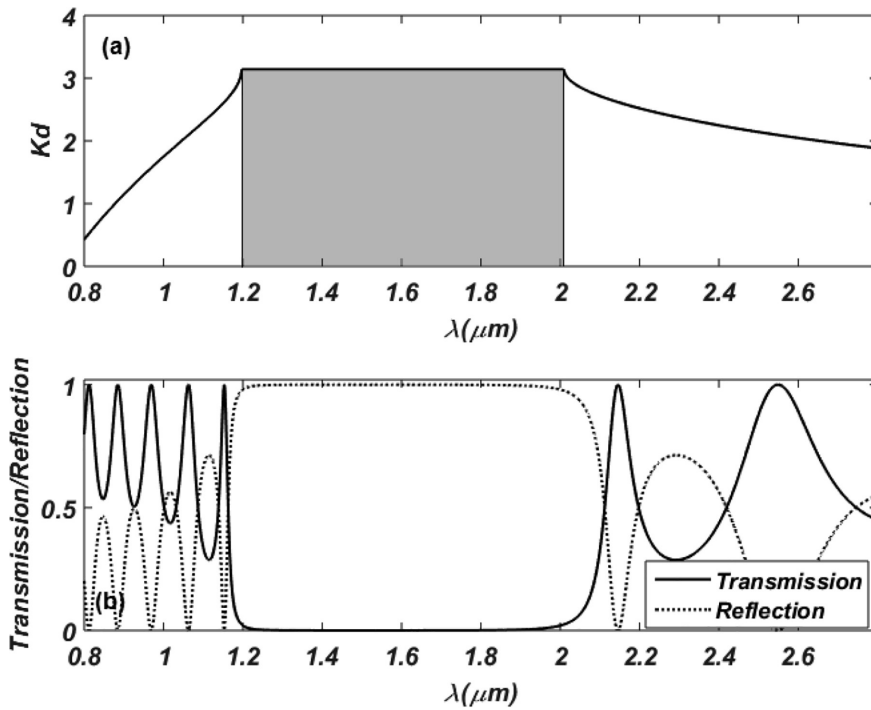


FIGURE 8.12

(a) Dispersion behavior of the 1D PC, that is, Kd vs wavelength (μm) plot; (b) transmission (solid line) and reflection spectra of 1D PC of Si and glass materials with structure $(\text{Si}|\text{Glass})^6$.

It is well known that the bandgap of the PC may be tunable by introducing the other dielectric materials as a defect inside the PC. The LC and graphene materials are taken as defect materials, which are most important in optics due to which optical behavior is controlled by an external parameter as discussed earlier.

We know that the orientation of LC molecules depends on the threshold wave intensity (Freedericksz transition). When the incident light wave intensity equals to or greater than the threshold value, then the molecules orient. For increasing intensity ratio, molecules follow particular direction, making the director angle maximum, whereas for decreasing intensity ratio, molecules follow the different path to reorientation due to existing new threshold for decreasing intensity as shown in Figure 8.13. Thus there exists a hysteresis loop for such orientation–reorientation, which reveals that the energy loss takes place in the process.

Now the 1D PC structure of Si and glass materials $(\text{Si}|\text{Glass})^6$ produced a defect by inserting the NLC layer asymmetrically. The NLC defect of 1D PC is shown in Figure 8.14. Using TMM (Yeh 1988), we calculate the transmittance of the $(\text{Si}|\text{Glass})^3|\text{NLC}|(\text{Si}|\text{Glass})^3$ structure at director angle 0° – 90° of the LC as shown in Figure 8.15. The transmission behavior of $(\text{Si}|\text{Glass})^3|\text{NLC}|(\text{Si}|\text{Glass})^3$ structure shows two defect peaks that obtain different orientations of LC molecule (Berezin et al. 1973). There is a shifting of defect peak with the orientation of the LC molecule, which helps to fabricate the tunable optical device in the microwave region. This study shows that the defect of NLC in the PC has the defect peaks at low wavelength region with high transmittance for 0° orientation of the NLC.

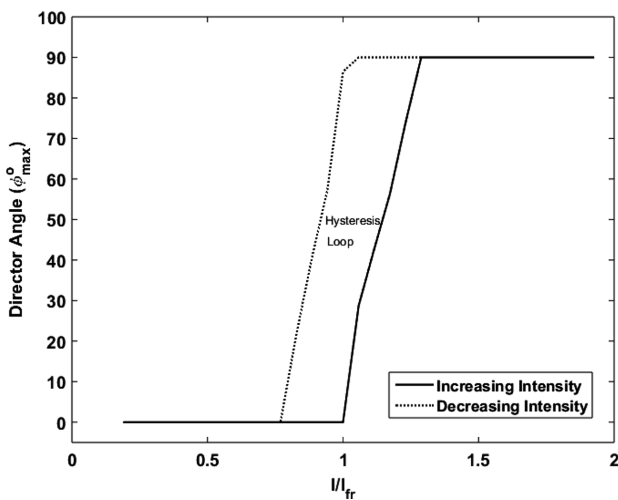


FIGURE 8.13
The behavior of LC director with intensity ratio for both cases increasing intensity (solid lines) and decreasing intensity (dashed lines).

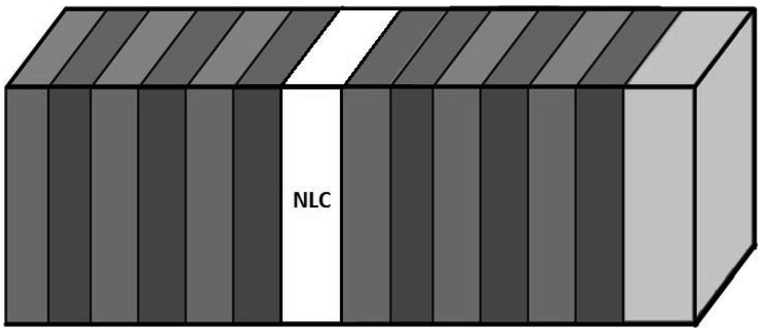


FIGURE 8.14
Schematic periodic structure of the Si/glass dielectric materials with the defect of LC.

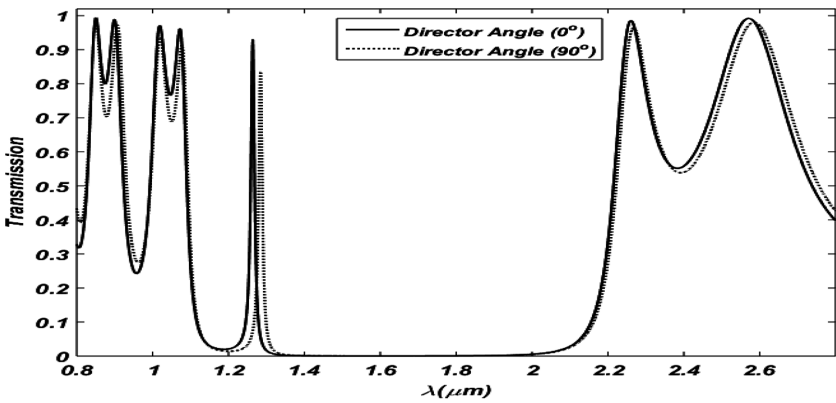


FIGURE 8.15
Transmission behavior of $(\text{Si}|\text{Glass})^3|\text{NLC}|(\text{Si}|\text{Glass})^3$ at director angle 0° – 90° .

We have a new periodic structure $(\text{Si}|\text{Glass})^3|\text{G}|\text{NLC}|\text{G}|(\text{Si}|\text{Glass})^3$ with a graphene layer G and have constructed with the stuck graphene layer at one end of the asymmetric finite 1D PC. The two asymmetrically finite 1D PCs with stuck graphene layers are embedded LC as the defect as shown in Figure 8.16.

The transmission spectra of the considered periodic structures $(\text{Si}|\text{Glass})^3|\text{NLC}|(\text{Si}|\text{Glass})^3$ and $(\text{Si}|\text{Glass})^3|\text{G}|\text{NLC}|\text{G}|(\text{Si}|\text{Glass})^3$, where G is the graphene layer, are calculated and compared (Figure 8.17). In the transmission spectra, two defect peaks at the low wavelength region are obtained for director angles 0° – 90° of the LC. The transmission of the defect peaks for director angle 0° and 90° is 92% and 82%, respectively. In the transmission spectra, there is shifting of defect peak in the PBG region. Figure 8.17b shows that the presence of graphene layers in the periodic structure affects the transmission spectra of 1D PC. The transmission of the structure in the presence of graphene layers is low in comparison to Figure 8.17a, which means graphene has high absorption property due to its semi-metallic nature and absorbs the small fraction of defect peaks in the transmission spectra.

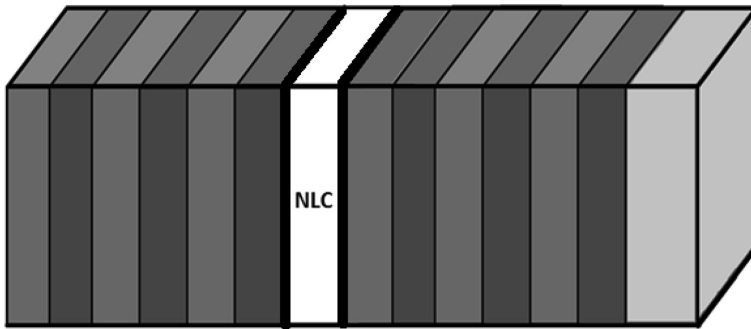


FIGURE 8.16

Schematic of defect of LC-embedded graphene layers (dark gray) in asymmetric periodic structure of the Si/glass dielectric materials $(\text{Si}|\text{Glass})^3|\text{G}|\text{NLC}|\text{G}|(\text{Si}|\text{Glass})^3$.

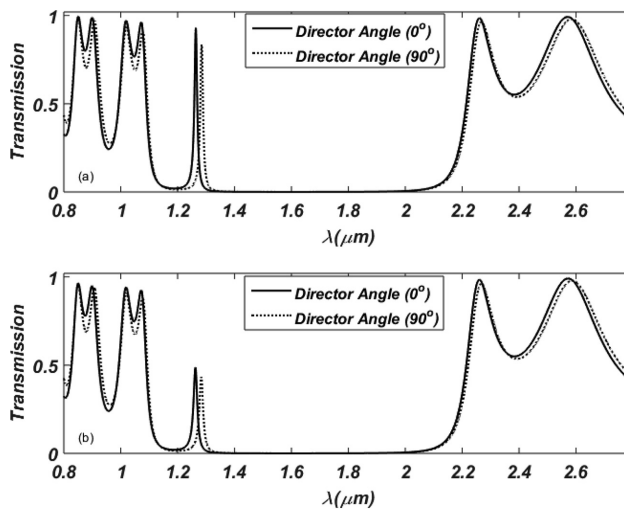


FIGURE 8.17

Transmission spectra at director angle 0° – 90° (a) $(\text{Si}|\text{Glass})^3|\text{NLC}|(\text{Si}|\text{Glass})^3$ and (b) $(\text{Si}|\text{Glass})^3|\text{G}|\text{NLC}|\text{G}|(\text{Si}|\text{Glass})^3$.

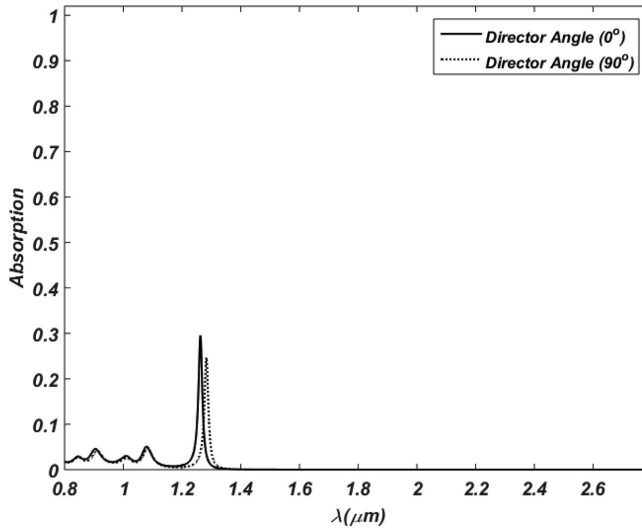


FIGURE 8.18
Absorption behavior of $(\text{Si}|\text{Glass})^3|\text{G}|\text{NLC}|\text{G}|(\text{Si}|\text{Glass})^3$ director angle 0° – 90° .

The absorption of the behavior of the $(\text{Si}|\text{Glass})^3|\text{G}|\text{NLC}|\text{G}|(\text{Si}|\text{Glass})^3$ is given by [Figure 8.18](#). In [Figure 8.18](#), the absorption for defects peaks is found to be 30% and 20% and may be used as a sensor.

8.4 Conclusions

The optical properties of the 1D PC with a defect of LC, where it is sandwiched with stuck graphene layers in the asymmetrically periodic structure of Si and glass materials, have been investigated. Our calculations show that the PC with the defect of LC is given a defect peak in the PBG region of the 1D PC with low absorption and affected the orientation of NLC director. The NLC is embedded with graphene layers in asymmetrically 1D PC and calculated the transmission of 1D PC with the defect of LC. We obtained the same defect peaks with the large absorption in the same PBG region. The high absorption of the structure gets affected with the presence of graphene layers. The transmission of defect peaks becomes low, and the absorption of defect peaks becomes enhanced due to the presence of graphene layers. The embedded NLC in the graphene layers in asymmetrically 1D PC is used as tunable optical devices, bistable switches, sensors, and optical filters.

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Tunable Broadband Reflector Using a One-Dimensional Photonic Crystal Containing Metamaterial with Symmetrically Introduced Magnetized Cold Plasma Defect

Asish Kumar, Khem B. Thapa, Narendra Kumar, and Anil K. Yadav

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9.1 Introduction

Photonic crystals (PCs) are artificial periodic nanostructures and microstructures containing dielectric, metallic, superconductor, and plasma materials, where the refractive index changes periodically in space. In 1987, PCs were experimentally introduced by Yablonovitch and theoretically proposed by John in the same year (John 1987; Yablonovitch 1987). Such kind of periodic structures affects the propagation of electromagnetic (EM) wave and produces bandgaps due to the periodicity of the materials. It is similar to the motion of an electron in the semiconductor material, which produces electronic bandgaps due to the periodic potentials. The wave propagation inside the periodic structure depends upon frequency of incident EM wave. Frequencies that are allowed to propagate are known as modes, and groups of allowed frequency modes constitute bands. In contrast, forbidden frequency ranges are called photonic bandgaps (PBGs), which are also known as Bragg's gaps because they are originated from the Bragg scattering in the periodic structures (Fink et al. 1998; Chigrin et al. 1999; Wu et al. 2003; Aghajamali et al. 2016).

In 1968, Veselago et al. theoretically predicted that electric permittivity and magnetic permeability of the materials are the fundamental characteristics, and they determine the propagation of EM waves in the matter (Veselago et al. 1968). The materials are called metamaterials or negative index materials (NIMs) or double-negative (DNG) materials, which have simultaneously negative values of the electric permittivity and the magnetic permeability. However, if both the electric permittivity and the magnetic permeability of the material are positive, then it is known as double-positive (DPS) material. According to

Kramers–Kronig relation, metamaterials are not only dispersive but also lossy materials. So, the refractive index of metamaterial is to be a complex value. The real part of refractive index shows the propagation of the wave, and the imaginary part of the refractive index shows the attenuation or decay of the wave (Gerardin et al. 2002; Zhang et al 2002; Li et al. 2003; Wu et al. 2003; Sabah et al. 2007; Lin et al 2010; Aghajamali et al. 2014a). The periodic structures of DNG and DPS materials are called PCs. Such PCs also exhibit the two types of the bandgaps: zero-index gaps and Bragg's gap, due to the thickness, refractive index contrast, and the chosen incident angle (Jhu et al. 2010).

Plasma photonic crystal (PPC) is a periodic array composed of alternating thin plasma and dielectric material/vacuum. Due to the periodicity of thin plasma and dielectric materials, plasma PBG is found. The band structure of one-dimensional (1D) PPC has appeared in the dispersion relation of the EM wave, which is tuned by the magnetic field, electron density, collision frequency, and thickness of the plasma layer. Booker (1984) investigated that the characteristics of magnetized cold plasma are not only dependent on electron density, effective collision frequency, and gyro-effective frequency of the plasma, but its gyro-effective frequency is also dependent on the applied magnetic field. The right-hand polarization (RHP) and left-hand polarization (LHP) of magnetized cold PPCs have negative and positive values of the gyro-effective frequency, respectively (Hojo et al. 2003; Hitoshi et al. 2004; Aghajamali et al. 2015). Therefore, the PCs of the metal or dielectric materials may be replaced by plasma for better controlled optical properties of the PCs, and such periodic structure of dielectric and PC is called 1D magnetized cold plasma PC. Kong et al. (2010) discussed the transmittance of the 1D PC doped with magnetized cold plasma under the transverse electric (TE) wave and shown the formation of narrow tunable band filter due to the magnetized plasma defect (Kumar et al. 2012; King et al. 2015).

Recently, several research papers have been reported the optical properties of defect mode of the plasma in a 1D PC. Aghajamali et al. (2016) investigated the transmission properties of 1D single negative (SNG) PC with the defect layer of magnetized cold plasma. They have shown that the thickness, electron density, and magnetic field of the PCs were affected the frequency bands of the 1D magnetized cold PPC. The tuned frequency of the defect mode with variations in the thickness of the magnetized cold plasma layer was found better than the variations of the magnetic field, electron density, and effective collision frequency of magnetized cold plasma.

Aly et al. (2017) studied the transmittance of 1D defective PPCs for transverse magnetic waves in the frequency range of GHz and have shown that the electric permittivity of the plasma layer was strongly affected by the external magnetic field of magnetized cold plasma. The external magnetic field has a great effect on the position and intensity of the defect modes. The transmission property of defect mode was also controlled by the plasma density, thickness of plasma layer, and angle of incidence. Hence, 1D defective PPCs for transverse magnetic waves could be used in many potential applications such as filter and sensors.

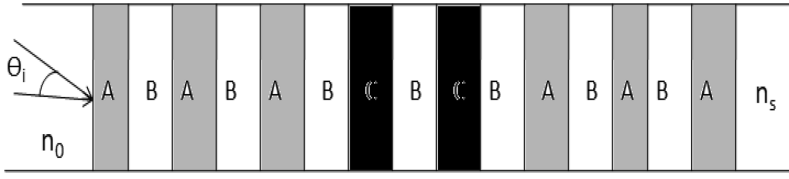
Recently, Nayak et al. (2017a) studied the transmittance of the defective 1D random extrinsic PPC with varying randomness and suggested that the thickness of the extrinsic plasma layer is determined using the Gaussian distribution. The wider PBG was found when the randomness is increased. Moreover, the number and the strength of resonant peaks of the random extrinsic PPCs were enhanced by the randomness of the extrinsic plasma layers. They have also suggested that the feature of such disordered extrinsic PPC structure has many potential applications in random channel filters with the low and high rates of the disorder. The defect of the extrinsic magnetized cold plasma with Gaussian

distribution provided random layer thickness, and photonic quantum-well structures were also reported (Nayak et al. 2017b). The histogram of defect mode frequency was shifted when the magnetic field is increased, whereas the electron density of the magnetized plasma is decreased. Their results are useful in the fabrication of energy sufficient to single-channel optical switch in the microwave regions. The defective PCs may consider a symmetric and asymmetric structure, and their optical properties may have special optical characteristics by varying the material's parameters (Aghajamali et al. 2014b). Recently, the theoretical study of DNG and DPS materials with magnetized cold plasma defect and the theoretical study of dielectric and silicon dioxide with a defect of one, two, and three layers of magnetized cold plasma were suggested for optical applications (Kumar et al. 2018b). The recent research proposed an innovative concept for the design of tunable and broadband reflector and narrowband filter with dielectric and magnetized cold plasma periodic structure (Kumar et al. 2018a). The 1D ternary periodic structure containing dielectric, plasma, and superconductor acts as tunable broadband filter and reflector at lower and higher frequency ranges (Kumar et al. 2018c). We know that the optical properties of the PC are dependent on the refractive index of the materials. According to the Maxwell's equations, the refractive index also depends on the electric permittivity and the magnetic permeability of the materials.

In our study, we calculate the variation of electric permittivity, magnetic permeability, and refractive index of the metamaterial against frequency. The study of optical properties of the 1D PC containing metamaterial shows the existence of the zero-index gap and Bragg's gap. We study the variations of these gaps with the thickness of metamaterial and angle of incidence, and also the optics of the magnetized cold plasma material and frequency dependence are studied. Then, we also study the transmittance of considered symmetrical structures with defect of dielectric and magnetized cold plasma. The 1D PC with symmetrically introduced defect of magnetized cold plasma has two types of structures: (i) PC with RHP defect and (ii) PC with LHP defect (Booker 1984; Yeh 1988; Zhang et al. 2007). The symmetrical 1D PC structure is represented by $(AB)^3(BA)^3$. Such 1D PC containing dielectric and metamaterial is made of three dielectric defect layers, and the periodic structure with dielectric defect is $(AB)^3BBB(BA)^3$. Now, two dielectric defect layers in the structure $(AB)^3BBB(BA)^3$ are replaced by the magnetized cold plasma layers and new 1D PC is represented by $(AB)^3CBC(BA)^3$, where A, B, and C are metamaterial, dielectric, and magnetized cold plasma (MCP), respectively. The transmittance, reflectance, and absorption spectra of the 1D PC with symmetrically introduced magnetized cold plasma defect are studied with the variations of electron density, magnetic field, and effective collision frequency of magnetized cold plasma. Such study will be very innovative to design the optical devices such as tunable filter and reflector.

9.2 Theoretical Concept and Methodology

The optical properties of 1D PC containing dielectric and metamaterial as periodic layers with and without a defect are studied using simple transfer matrix method (TMM), which is a very useful tool to calculate the all-optical properties of 1D PC containing dielectric and metamaterial with and without a defect. The 1D PC is constituted with the alternative layers of metamaterial and dielectric materials. The symmetrically introduced defective MCP in 1D PC is shown in [Figure 9.1](#).

**FIGURE 9.1**

Schematic of one-dimensional photonic crystal containing metamaterial and dielectric with symmetrically introduced dual magnetized cold plasma (MCP).

The electric permittivity and the magnetic permeability of the metamaterial (A) are calculated by the following expression (Aghajamali et al. 2014b):

$$\begin{aligned}\varepsilon(\omega) &= 1 + \frac{5^2}{0.9^2 - \omega^2 - i\omega\gamma_e} + \frac{10^2}{11.5^2 - \omega^2 - i\omega\gamma_e}, \\ \mu_A(\omega) &= 1 + \frac{3^2}{0.90.2^2 - \omega^2 - i\omega\gamma_m},\end{aligned}\quad (9.1)$$

where ε_A and μ_A are the permittivity and the permeability of the layer metamaterial (A), ω is the angular frequency in GHz, and γ_e and γ_m are the electric and magnetic damping frequencies.

Now, C is the MCP layer, and its complex electric permittivity and magnetic permeability is expressed as follows:

$$\varepsilon_c(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 \left(\left(1 - i \frac{\gamma}{\omega} \right) \mp \frac{\omega_{le}}{\omega} \right)} \text{ and } \mu_c = 1, \quad (9.2)$$

where ω , γ , and ω_{le} are the angular, effective collision frequency, and gyro-effective collision frequencies, respectively, and ω_{pe} is the plasma frequency. The plasma frequency is dependent on the electron density and is given by the following:

$$\omega_{pe} = \left(\frac{n_e e^2}{m \varepsilon_0} \right)^{1/2}, \quad (9.3)$$

where n_e , m , ε_0 , and e are the electron density, electronic mass, permittivity in free space, and electronic charge, respectively, and the gyro-effective frequency is expressed as follows:

$$\omega_{le} = eB / m, \quad (9.4)$$

where B is the external magnetic field.

When ω_{le} is negative, the value of B is positive, then the plasma defect structure acts as RHP, and when ω_{le} is positive, the value of B is negative, then the plasma defect structure acts as LHP (Aghajamali et al. 2015, Booker 1984). Solving the Maxwell equation and applying boundary conditions at each interface of the material, we study the optical property of PC used as a metamaterial with MCP defect (Engheta 2006, Smith 2000).

The characteristic matrix of each layer is represented by M_i and is used to calculate the transmission, reflection, and absorption spectra of the layer for the TE wave at incident angle θ_0 from vacuum and is given by the following:

$$M_i = \begin{bmatrix} \cos \gamma_i & -\frac{i}{p_i} \sin \gamma_i \\ -ip_i \sin \gamma_i & \cos \gamma_i \end{bmatrix} \quad (9.5)$$

where $\gamma_i = (\omega/c) n_i d_i \cos \theta_i$, c is the speed of light in vacuum, θ_i is the ray angle inside i th layer with a refractive index as $n_i = \sqrt{\mu_i \epsilon_i p_i} = \sqrt{\frac{\epsilon_i}{\mu_i}} \cos \theta_i$ and $\cos \theta_i = \sqrt{1 - \frac{n_0^2 \sin^2 \theta_0}{n_i^2}}$ in which n_0 is the refractive index of air, where the incidence wave tends to enter the layer or material. The refractive index of the layer is given as $n_i = \sqrt{\mu_i \epsilon_i}$ in which positive sign is for the DPS material, whereas the negative sign is for the DNG material.

Using this characteristic matrix for the each layer, the characteristic matrix for periodic structure may be written, which is the most important method to analyze the transmission, reflection, and absorption properties of the 1D PC containing dielectric and metamaterial with and without a defect. The characteristic matrix is given as follows:

$$M_{i,j} = \begin{pmatrix} m_{1,1} & m_{1,2} \\ m_{2,1} & m_{2,2} \end{pmatrix}, \quad (9.6)$$

where $M_{i,j}$ with $i, j = 1, 2$ are the matrix elements of the whole periodic structure. Using basic concept of the optics, the transmission coefficient of the PC containing dielectric and metamaterial with and without a defect is calculated by the following:

$$t = \frac{2p_0}{(m_{11} + m_{12}p_s) + (m_{21} + m_{22}p_s)}. \quad (9.7)$$

The reflection coefficient of 1D PC containing dielectric and metamaterial with and without a defect is calculated by the following:

$$r = \frac{m_{11}p_0 - m_{12}p_0p_s + m_{21} - m_{22}p_s}{m_{11}p_0 + m_{12}p_0p_s + m_{21} + m_{22}p_s}, \quad (9.8)$$

where $p_0 = n_0 \cos \theta_0$ and $p_s = n_s \cos \theta_s$, n_s is the refractive index of the air, whose ray angle is θ_s .

The transmission spectra of 1D PC containing dielectric and metamaterial with and without a defect is given by the following (Yeh 1988):

$$T = \frac{p_s}{p_0} |t|^2. \quad (9.9)$$

The reflection spectra of 1D PC containing dielectric and metamaterial with and without a defect is given by the following:

$$R = |r|^2. \quad (9.10)$$

The absorption spectra of the 1D PC containing dielectric and metamaterial with and without a defect is calculated by the following:

$$A = 1 - R - T. \quad (9.11)$$

9.3 Results and Discussion

The electric permittivity and the magnetic permeability of the metamaterial are evaluated from equation (9.1). The electric and the magnetic loss factors are taken as $\gamma_e = \gamma_m = 0.2 \times 10^{-3}$ GHz (Aghajamali et al. 2015). Figure 9.2a shows the variation of electric permittivity and magnetic permeability against frequency simultaneously. The zero values of the electric permittivity and magnetic permeability are found at the frequency range of 0.50–0.60 GHz. The positive values of the electric permittivity and magnetic permeability are shown at the —frequency range of 0.70–1.60 GHz. However, the electric permittivity and the magnetic permeability have negative values below 0.50–0.60 GHz frequency range simultaneously and have negative refractive index of the metamaterial, which is very unusual.

The refractive index of the metamaterial for the corresponding frequency range of ϵ and μ is shown in Figure 9.2b. Figure 9.2 shows that the electric permittivity and the magnetic permeability of metamaterial have zero values at 0.50 and 0.60 GHz, respectively.

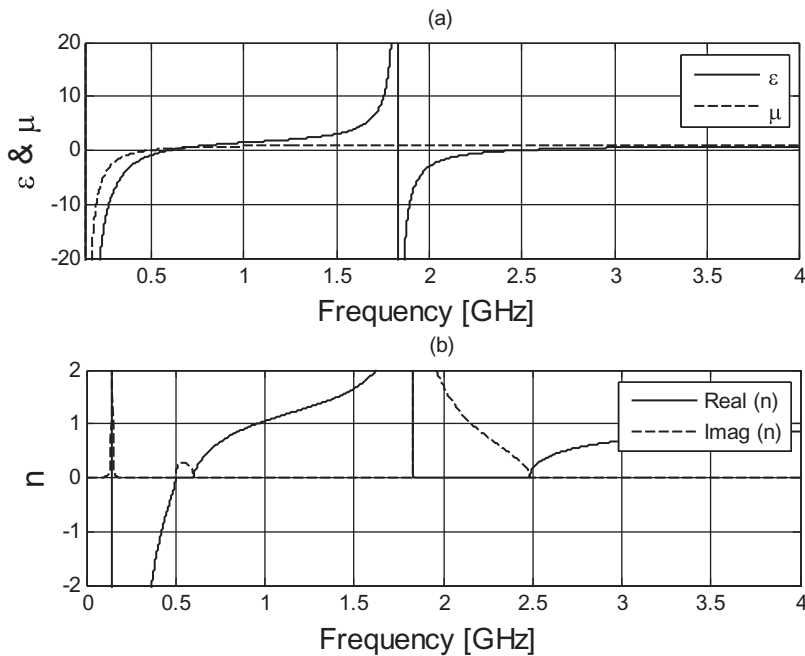


FIGURE 9.2

Optical constants of the metamaterial versus frequency plots for (a) electric permittivity and magnetic permeability and (b) refractive index.

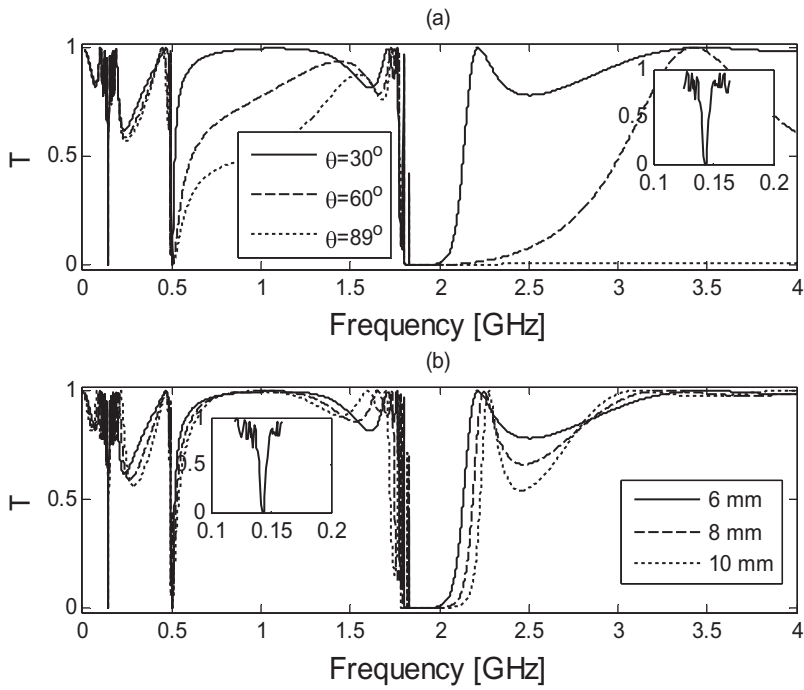
The refractive index approaches to zero value in the frequency range between 0.50 and 0.60 GHz. The electric permittivity and the magnetic permeability have positive values above this frequency range, but the magnetic permeability is nearly zero up to 1.83 GHz. The refractive indices of the metamaterials are negative, zero, and positive in the frequency range of 0.14–0.50, 0.50–0.60, and 0.60–1.80 GHz, respectively.

Now, this metamaterial is used to construct PC that has the periodic structure of the metamaterial (A) and dielectric (B). The thicknesses of the A and B materials are 6 and 12 mm, respectively. The refractive index of the metamaterial is similarly taken as discussed in the previous section. The dielectric layer B is considered as vacuum (air) medium with refractive index $n_B = 1$. The total number of the lattice periods is considered to six, that is, $N = 6$. Using these parameters, we have calculated the transmittance of the PC and show three types of bandgaps: (i) zero gap at the low frequency range, (ii) Bragg's gap at the high frequency range, and (iii) some new bandgap in between the zero-index gap and Bragg's gap as shown in Figure 1.3. To verify the zero gap and Bragg's gap of the structure, we have calculated the transmittance with variable incident angles and the thicknesses of the metamaterial (Li et al 2003; Singh et al 2007).

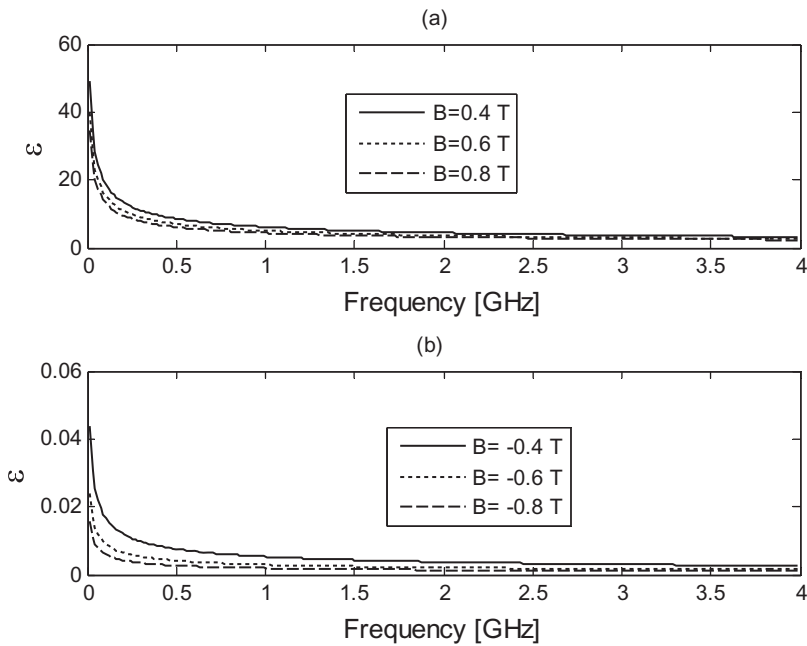
Figure 1.3a is demonstrated the transmission spectra against frequency for the PC with variable angle of incidence for $\theta = 30^\circ$, $\theta = 60^\circ$, and $\theta = 89^\circ$ and has predicted transmittance-dependent properties for the bandgaps. The transmittance at the lower frequency does not vary with the incident angles, but the transmittance at the higher frequency is highly affected with the incident angles. The lower frequency range of the transmission spectra is represented as the zero bandgap due to zero refractive index of the metamaterials.

The higher frequency range of the transmission spectra represents Bragg's gap due to a positive refractive index of the metamaterials. The obtained results predict the zero-index and Bragg's gap in the frequency range of 0.132–0.142 and 1.80–2.00 GHz, respectively. In between, these two bandgaps and the transmittance are also changed with the variation in the angles of incidence, $\theta = 30^\circ$, 60° , and 89° , which are called new bandgap and produced due to combined properties of zero- ϵ and zero- μ of the metamaterial (Singh et al 2007). Similarly, we have studied the transmittance by varying of the thicknesses of the metamaterial. Figure 9.3b shows the plot of transmittance against frequency by varying thicknesses of metamaterials 6, 8, and 10 mm. These studies reveal that the transmittances are similar to previous calculations, but the new bandgap has minute variation with thicknesses. The zero-index gaps are independent of angle of incidence as well as the thickness of metamaterial. However, Bragg's gap is dependent on both parameters, as shown in Figure 9.3. The new bandgap is the combined properties of zero- ϵ and zero- μ of the metamaterial, which is also affected with variation in the angles of incidence and the thicknesses of the metamaterial.

As discussed earlier, the MCP is used in several optical devices having the variable parameters. The variations of electric permittivity of the MCP layer, with different values of the external magnetic field, are studied from equation (9.2) as shown in Figure 9.4. We know that the magnetic cold plasma has two types due to change in the direction of the applied magnetic field. The electric permittivity of the RHP has a huge variation in comparison with the LHP as shown in Figure 9.4a and b. The electric permittivity of the RHP for low magnetic field is very high at the low frequency range. However, the electric permittivity of the RHP for low magnetic field in the opposite direction is high at the low frequency range compared with the other applied fields. The optics of the MCP is used in the considered periodic structure.

**FIGURE 9.3**

Transmittance versus frequency plots with varying (a) angle of incidence wave and (b) thickness for the metamaterial.

**FIGURE 9.4**

Optical constants of MCP versus frequency plots for (a) electric permittivity for RHP and (b) electric permittivity for LHP.

Now, we are interested to see the optical property of the defect of dielectric as well as MCP in the symmetrical periodic structure. The optical properties of the 1D PCs, $(AB)^3BBB(BA)^3$ and $(AB)^3CBC(BA)^3$, where A, B, and C are the metamaterial, dielectric, and MCP layers, respectively, are studied using TMM. Here, the thicknesses and the refractive indices of layer A and B are same as previous calculations. The thickness of the MCP is taken as 15 mm, and the refractive index of the MCP is taken from Equation (9.2). The MCP layers are introduced in the $(AB)^3BBB(BA)^3$ structure in such a way that the dielectric layer is sandwiched by MCP defect layers, that is, structure has now the form of $(AB)^3CBC(BA)^3$. The transmittance of the considered defect structures shows two types of the gaps: zero index and Bragg's. In between these bands, first, a new bandgap is disappeared, but second, some new bandgap near the zero gap is existed for the $(AB)^3BBB(BA)^3$ structure as shown in Figure 9.5a. The transmittance of considered PC with symmetrical defect of three dielectric layers also shows zero bandgap, Bragg's gap and new bandgap near the zero gap. The Bragg's gap with 100% transmittance of the structure shows two sharp peaks at the band edges due to the thickness of defective dielectric materials.

Similar calculation for transmittance of the PC with MCP defect is calculated. The study shows that the transmittance in between the zero-index and Bragg's gaps of the considered structure is decreased due to MCP layers, that is, the reflectance of the $(AB)^3CBC(BA)^3$ with MCP is increased.

Now, we have studied the transmission spectra of the same structure inserted with two MCP layers instead of the dielectric layers as shown in Figure 9.1. The thicknesses of the both MCP layers are taken as 15 mm and other parameters such as loss factor $\gamma = 0.2 \times 2\pi \times 10^{-2}$ GHz, external magnetic field $B = 0.4$ T, and the electron density of the

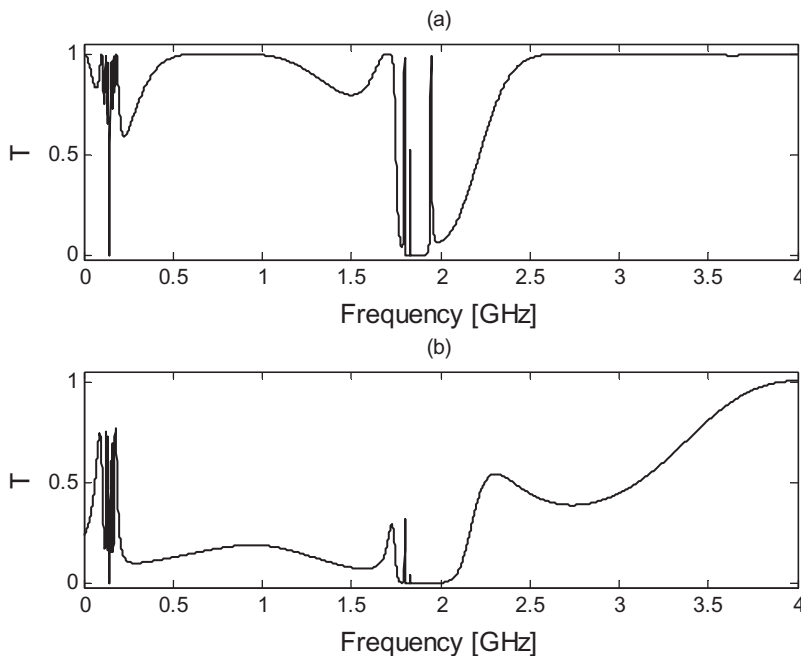


FIGURE 9.5

Variations of the transmittances of 1D PC structures with two types of defects: (a) $(AB)^3BBB(BA)^3$ and (b) $(AB)^3CBC(BA)^3$.

MCP $n_e = 8 \times 10^{17}/\text{m}^3$ are taken for calculating the refractive index of the MCP. Using the above parameters, we calculate transmittance of the structure against frequency as shown in Figure 9.5b. The transmission spectra shows that the positions of both bandgaps are not changed, but the transmittance is highly reduced due to having loss factor of the plasma layer. The bandgap possesses 20% transmittance peaks at the band edges. Moreover, the effect on bandgap is studied due to the plasma parameters such as magnetic field, electron density, and effective collision frequency. The high reflectance of the PC with dual MCP layers is obtained, that is, low transmission.

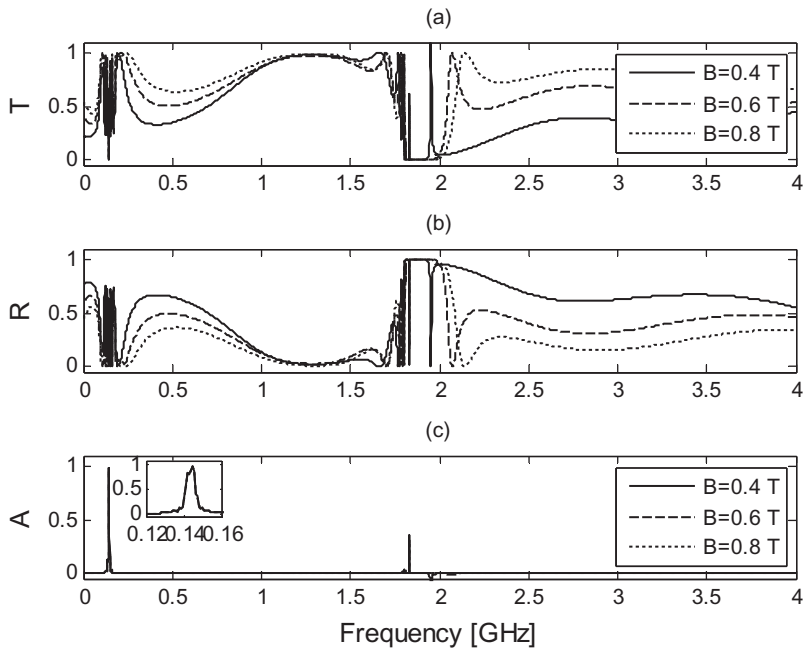
Above calculation shows that the transmittance of the 1D PC with MCP defect layers is more effective than the transmittance of the PC with dielectric defect layers. Besides this, the high transmittance for $(\text{AB})^3\text{BBB}(\text{BA})^3$ structure is obtained while there is low transmittance for $(\text{AB})^3\text{CBC}(\text{BA})^3$ structure. This gap between the zero-index and Bragg's gap shows a partially broadband reflector behavior due to the presence of the MCP.

Now, we focus on the transmission, reflection, and absorption spectra of the defect layers of MCP due to interesting behavior with varying most valuable parameters such as external magnetic field (B), electron density (n_e), and effective collision frequency (γ), which show interesting behaviors of the considered structure. The refractive index of RHP and LHP is tunable, and by changing the direction of the applied magnetic field in the MCP layers of the $(\text{AB})^3\text{CBC}(\text{BA})^3$, we have considered two structures: (i) RHP structure and (ii) LHP structure as discussed earlier. The transmission, reflection, and absorption spectra for two different structures with applied magnetic field of the MCP have considered under TE wave polarization at normal incidence i.e. $\theta = 0^\circ$.

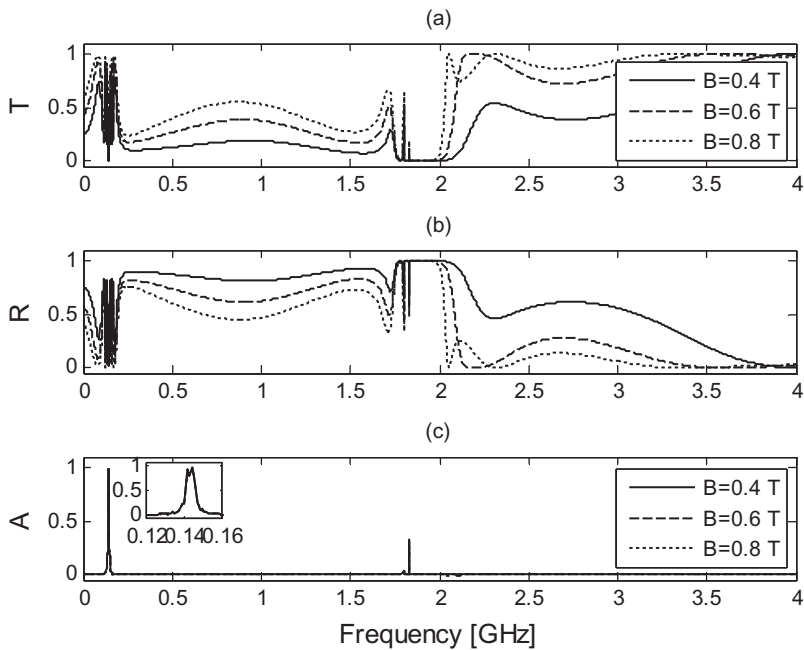
The transmission, reflection, and absorption spectra of the RHP structure is calculated by varying magnetic field $B = 0.4, 0.6, 0.8$ T with fixed $n_e = 8 \times 10^{17}/\text{m}^3$ and $\gamma = 2\pi \times 10^{-2}$ GHz as shown in Figure 9.5. The transmission and reflection spectra between zero-index gap and Bragg's gap have changed correspondingly for magnetic field $B = 0.4, 0.6, 0.8$ T. Figure 9.6a shows that the transmission spectra vary between zero-index gap and Bragg's gap. However, low transmission of the considered structure has been obtained at 0.2 GHz frequency near the zero gap and at 1.6 GHz frequency near Bragg's gap.

The high reflection spectra also occurs at the same frequency range but shows huge reflecting behavior of EM waves for low applied magnetic field as shown in Figure 9.6b. In contrast, the absorption spectrum of considered periodic structure is nearly zero. The 98% absorption at 0.13–0.15 GHz frequency is obtained inside zero-index gap as shown in inset plot. Similarly 35% absorption at 1.8 GHz frequency is also shown inside Bragg's gap (Figure 9.6c).

Similarly, the transmission, reflection, and absorption spectra against frequency are theoretically studied for LHP structure with variable negative magnetic field, that is, $B = -0.4, -0.6, -0.8$ T with fixed $n_e = 8 \times 10^{17}/\text{m}^3$ and $\gamma = 2\pi \times 10^{-2}$ GHz, as shown in Figure 9.7. The transmission spectra between zero-index gap and Bragg's gap is changed with applied magnetic field. The low transmission spectra between zero-index gap and Bragg's gap has been obtained for LHP with low value of magnetic field where only 20% light passes from the considered periodic structure as shown in Figure 9.7a. The reflection spectra between the zero-index gap and Bragg's gap against frequency with variable magnetic field of considered periodic structure are also changed. The reflection spectra of the considered periodic structure become approximately 85% for light reflected from the considered periodic structure for low value of magnetic field as shown in Figure 9.7b. The absorption spectra between zero-index gap and Bragg's gap against frequency with varying magnetic field has been nearly zero, but 100% absorption at 0.13–0.15 GHz frequency range is obtained inside the zero-index gap as shown in the inset and 35% absorption at 1.8 GHz frequency is found

**FIGURE 9.6**

Optical properties of the photonic crystal with right-hand polarization MCP defect: (a) Transmission spectra, (b) reflection spectra, and (c) absorption spectra, with varying applied magnetic field.

**FIGURE 9.7**

Optical properties of the photonic crystal with left-hand polarization MCP defect: (a) transmission spectra, (b) reflection spectra, and (c) absorption spectra, with varying applied magnetic field.

inside Bragg's gap for low value of magnetic field as shown in Figure 9.7c. The enhanced reflectance has the tunable characteristics due to MCP layers, which are very innovative investigation for potential application in optical devices.

Now, the transmission, reflection, and absorption spectra of RHP structure are studied against frequency with varying electron density $n_e = 4 \times 10^{17}/\text{m}^3$, $6 \times 10^{17}/\text{m}^3$, $8 \times 10^{17}/\text{m}^3$, with fixed $B = 0.4 \text{ T}$ and $\gamma = 2\pi \times 10^{-2} \text{ GHz}$ of MCP as shown in Figure 9.8. We have analyzed optical property of the RHP structure in between zero-index gap and Bragg's gap with variation of the electron density of MCP. The transmittance of the RHP structure shows the same variation as for the magnetic field in the previous calculations, but low transmission is found for high electron density of MCP. The transmittance is continuously decreased as the electron density of MCP is increased, that is, for high electron density of MCP has low transmittance. The low and high transmittances are found for high and low electron density at low frequency range as shown in Figure 9.8a. The transmittance of the RHP structure at 1.0–1.5 GHz frequency range is slightly changed in comparison with the lower frequency range due to change of the refractive index of the RHP. By varying plasma electron density of MCP, the new bandgap between the zero index bandgap and Bragg's gap has the tunable property due to variation of the transmittance of the RHP structure. Similarly, reflection spectra occurs in same frequency range with varying the electron density of MCP but shows reflection behavior of EM wave as shown in Figure 9.8b. The absorption spectra against frequency with varying electron density of MCP have behavior similar to the above absorption spectra by varying applied magnetic field and obtained the 98% absorption in zero-index gaps at 0.13–0.15 GHz frequency as shown in inset plot and 35% absorption in Bragg's gap at 1.8 GHz frequency as shown in Figure 9.8c.

Again, the transmission, reflection, and absorption spectra of the LHP structure, with varying electron density values of $n_e = 4 \times 10^{17}/\text{m}^3$, $6 \times 10^{17}/\text{m}^3$, and $8 \times 10^{17}/\text{m}^3$ with fixed

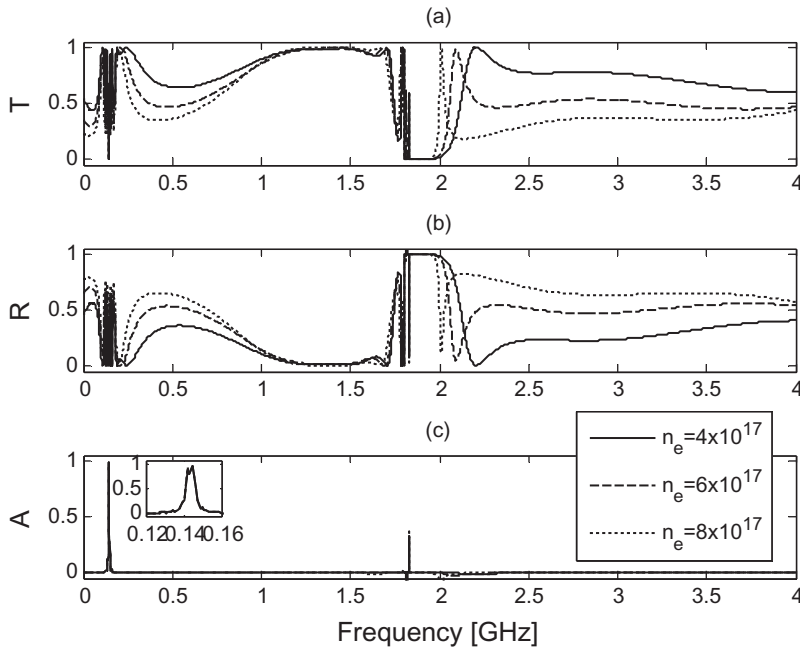
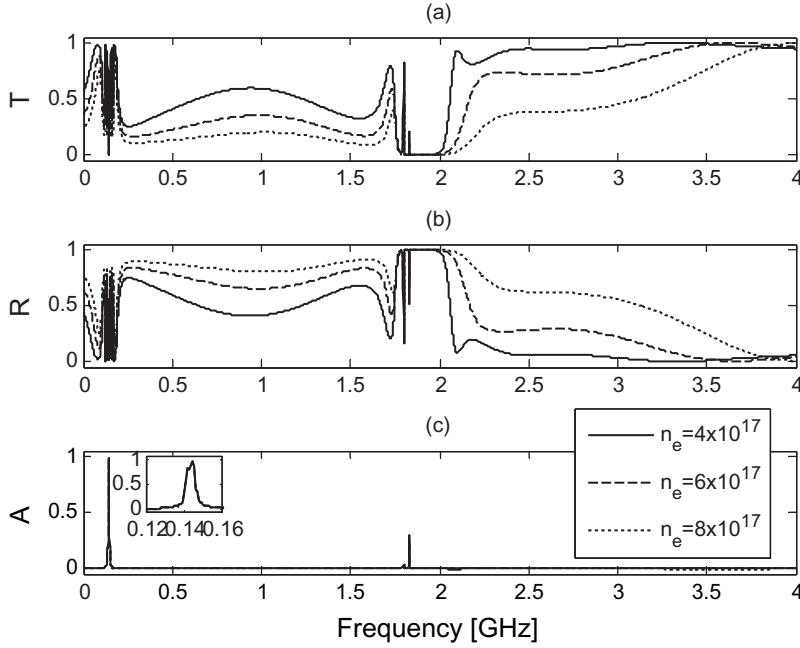


FIGURE 9.8

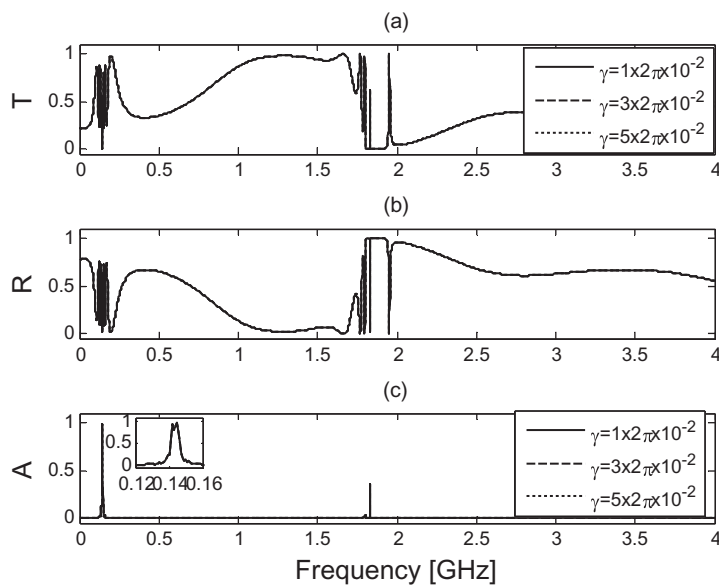
Optical properties of photonic crystal containing MCP defect with RHP: (a) transmission spectra, (b) reflection spectra, and (c) absorption spectra, with varying electron density.

**FIGURE 9.9**

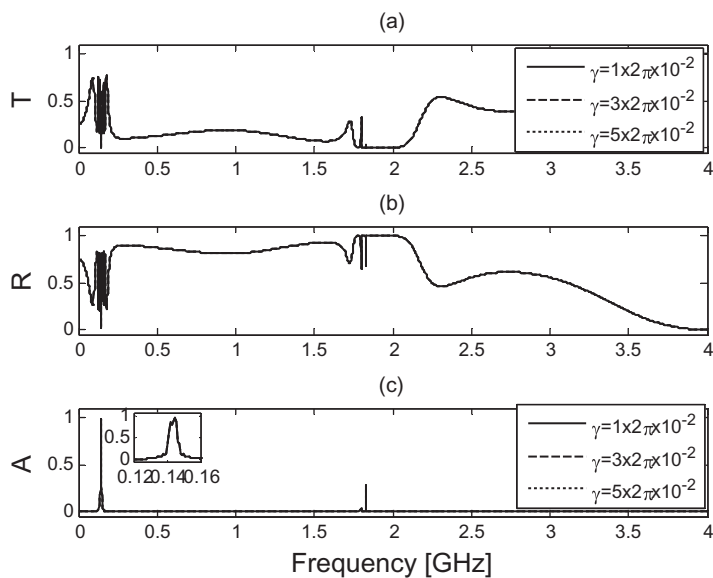
Optical properties of the photonic crystal containing MCP defect with LHP: (a) transmission spectra, (b) reflection spectra, and (c) absorption spectra, with varying electron density.

$B = -0.4$ T and $\gamma = 2\pi \times 10^{-2}$ GHz of MCP, are studied. The transmission spectra against frequency have been theoretically studied between the zero-index gap and Bragg's gap with variable plasma density for LHP structure. The transmission spectra become low at high value of plasma density as shown in Figure 9.9a. The reflection spectra of considered periodic structure are also studied with the varying electron density of MCP. Figure 9.9b shows the reflection spectra approximately 85% for the high value of plasma density. The absorption spectra, by varying electron density of MCP, have similar behaviors to the above absorption spectra with variation in the applied magnetic field and obtained 85% of absorption in zero-index gaps at 0.13–0.15 GHz frequency and 35% absorption in Bragg's gap at 1.8 GHz frequency for the RHP structure.

Finally, we have studied the transmission, reflection, and absorption spectra against frequency by varying effective collision frequency as $\gamma = 1 \times 2\pi \times 10^{-2}$ GHz, $2 \times 2\pi \times 10^{-2}$ GHz, $3 \times 2\pi \times 10^{-2}$ GHz with fixed $B = 0.4$ T and $n_e = 8 \times 10^{17}/\text{m}^3$ for RHP structure as shown in Figure 9.10. The transmission and reflection spectra of considered periodic structure also show variations with variation in effective collision frequency of MCP and the transmission and reflection behaviors are shown in Figure 9.10a b, respectively. The reflection spectra shows 80% light reflected for all values of effective collision frequency as shown in Figure 9.10b. The absorption spectra with varying effective collision frequency of MCP have similar behavior as in the case of varying applied magnetic field to the above absorption spectra and the 98% absorption at 0.13–0.15 GHz frequency range obtained inside zero-index gap and 35% absorption at 1.8 GHz frequency inside Bragg's gap for RHP structure. Similar study has been done for LHP, and the transmission spectra have also changed. 20% light transmits from the considered periodic structure for all values of effective collision frequency as shown in Figure 9.11a. The reflection spectra of considered periodic structure with varying effective collision frequency for LHP structure show that

**FIGURE 9.10**

Optical properties of the photonic crystal containing MCP defect with RHP: (a) transmission spectra, (b) reflection spectra, and (c) absorption spectra, with varying effective collision frequency.

**FIGURE 9.11**

Optical properties of the photonic crystal containing MCP defect with LHP: (a) transmission spectra, (b) reflection spectra, and (c) absorption spectra, with varying effective collision frequency.

approximately 85% light reflects from the considered structure as shown in [Figure 9.11b](#). Similarly, the absorption spectra have also shown same behavior as discussed in the above section. The inset plot of [Figure 9.11c](#) shows that there are 98% absorption at 0.13–0.15 GHz frequency range inside zero-index gap and 40% absorption at 1.8 GHz frequency inside Bragg's gap.

9.4 Conclusions

The optical properties of a 1D PC containing dielectric and metamaterial with and without a defect are theoretically studied. First, we have studied the transmittance of the 1D PC containing dielectric and metamaterial without defect and obtained zero-index gap and Bragg's gap at low and high frequency ranges, respectively. The zero-index gap and the Bragg's gap of the 1D PC are existed at the low (0.50 GHz) and high (0.60 GHz) frequencies. Between these gaps, a new PBG is also obtained. We have also shown that the zero-index gap is independent of the thickness of the metamaterial as well as the incident angle of the EM wave. The transmittance spectra of the 1D PC with dielectric defect have only zero-index and Bragg's gap, but the new bandgap is disappeared. However, the disappeared bandgap are found between zero index and Bragg's gaps. The disappeared new bandgap varies with the defect parameters of the MCP like the magnetic field, the plasma electron density and the effective collision frequency. We investigated the broaden reflector behavior of the PC with symmetrically introduced dual MCP defects due to high sensitivity of cold plasma on the variable parameters. The transmission spectra of the considered structures, with variable magnetic field plasma density and effective collision frequency, reveal that for the optical properties of the considered structure, these plasma parameters are highly effective in comparison to the other parameters of the metamaterial and dielectric material. The RHP and LHP structures are able to be tuned by the MCP parameters. However, the optical properties 1D PCs with MCP as a defect have shown the high reflectance with tenability behavior. The transmission and reflection spectra of the LHP structure have shown that the new bandgap is in the high reflectance or low transmittance range for low magnetic field and high plasma electron density. Our studies reveal that the LHP structure with low magnetic field and high electron density may be used as a tunable broadband reflector. Besides this, the high absorption is obtained inside the zero index and Bragg's gaps of all the defect structures. Such absorption property of the considered structure may be used in high absorption spectrum for solar cell and microwave absorber. The new gap of the 1D PC with symmetrically introduced MCP defect is tuned by varying most valuable parameters of the MCP. By varying the parameters of the MCP, 100% reflectance of the structure is converted into 0% reflectance. As our knowledge, our group has done such calculations first time. Such property of the 1D PC containing dielectric and metamaterial with symmetrically introduced dual MCP defect has many potential applications to design the tunable optical devices.

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10

Photonic Crystal-Based Sensors for Biosensing Applications

R. Rajasekar, G. Thavasi Raja, and Robinson Savarimuthu

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10.1 Introduction

The optical sensor is an analytical device used to convert the amount of analytes into a detectable signal and is also used for sensing applications such as industrial process control, military, environment monitoring, and medical diagnostics. It depends upon a phenomenon called the evanescent field to monitor changes in the refractive index occurring within a few hundred nanometers of the sensor surface (Vijayashanthi and Robinson 2014). The most of the optical sensors are ultracompact size, which is highly suitable for photonic integrated circuits and various sensing applications. Recently, fiber optic sensors have attracted the considerable attention due to their unique properties such as resistance to electromagnetic interference, high sensitivity, small sensing unit, safety in hazards or explosive environments, the possibility of processing the signal at large distances, and the ability to work under high temperature, and high pressure conditions (Zhao et al. 2000). However, the optical losses are increased due to the size reduction, which leads affect the performance of the sensor. The aforementioned issues are mitigated using the photonic crystal (PC) (Qiang et al. 2007).

Yablonovitch (1987) and John (1987) successfully proposed artificial periodic structures known as PCs and suggested that the periodic structure of dielectric with varying dielectric constant could influence the nature of photonic modes. Engineering of electromagnetic waves has done at various optical frequencies in PCs. The very first successful PC structure was presented in 1991. The idea of Yablonovitch and John was to design a material that can affect the properties of light in a same way as semiconductor affects the properties of electrons. This new class of optical material generally known as PCs holds the key of evolution toward all-optical-integrated circuits.

PCs are periodic nanostructures that are designed to affect the motion of photons in the same way as the periodic potential in a semiconductor crystal affects the electron motion by defining allowed and forbidden electronic energy bands (Yablonovitch et al. 1991). Generally, PCs are composed of periodic dielectric nanostructures that alternative lower and higher dielectric constant materials in one, two, and/or three dimensions to affect the propagation of light signal within a structure. As a result of this periodicity, the transmission of light is absolutely zero in certain frequency ranges called photonic bandgap (PBG). By introducing the defects (point defects or line defects or both) in these

periodic structures, the periodicity and thus the completeness of the PBG are entirely broken, which allows to control and manipulate the light (Joannopoulos et al. 1995). It ensures the localization of light in the PBG region, which leads to the design of the PC-based optical device.

10.2 Types of Photonic Crystals

PCs are classified mainly into one dimensional (1D), two dimensional (2D), and three dimensional (3D) according to its nature of structure periodicity.

The defining structure of a PC is the periodicity of dielectric material along one or more axis. The schematic of 1D PCs, 2D PCs, and 3D PCs is shown in [Figure 10.1a–c](#), respectively.

The wavelength selection and reflection properties in 1D PCs are used in a wide range of applications including high efficiency mirrors, optical filters, waveguides, and lasers. Also, such structures are widely used as antireflecting coatings, which dramatically decrease the reflectance from the surface and used to improve the quality of the lenses, prisms, and other optical components.

The 1D PC is periodic in single direction, and it is used for designing optical mirrors (Lin et al. 2010). The 2D PC is periodic in two directions and homogenous in third as it is used for designing filters (Robinson and Nakkeeran 2011), waveguides (Lin et al. 2004), sensors (Liu and Salemin 2012), logic gates (Singh and Rawal 2015), multiplexers (Lin et al. 2010), and demultiplexers (Niemi et al. 2006).

The 3D PC is periodic in three directions, which are used for designing optical lasers (Cao et al. 2012). Easiest fabrication of devices and complete PBG generation are the most important factors to select 2D PC platform. The 2D PC lattice structures are classified into triangular lattice and square lattice. Generally, 2D PCs consist of dielectric rods in air host or air holes in a dielectric region (low dielectric rods in a connected higher dielectric lattice) as shown in [Figure 10.2a, b](#).

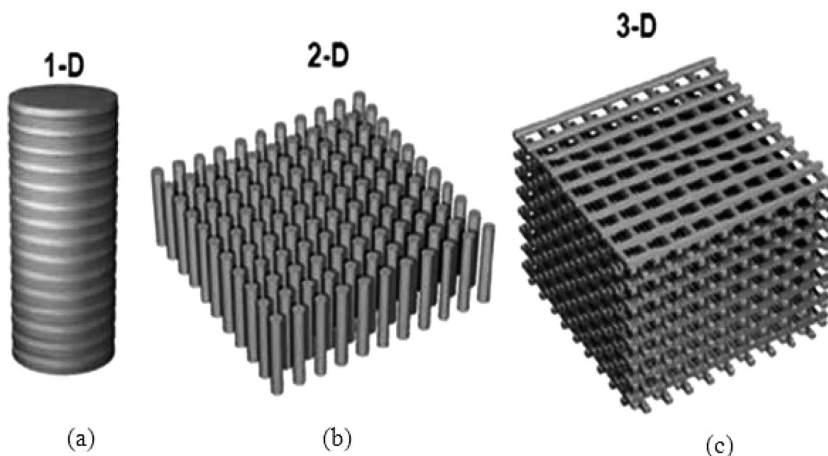


FIGURE 10.1
Schematic of (a) 1D, (b) 2D, and (c) 3D photonic crystals.

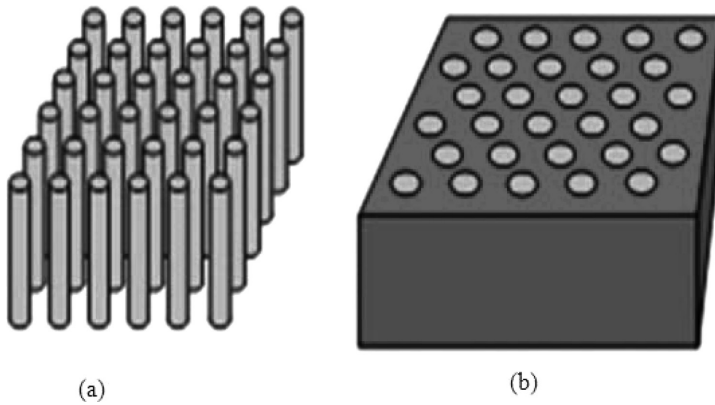


FIGURE 10.2
Structure of (a) dielectric rods in air and (b) air holes in dielectric region.

The dielectric rods in air host provide PBG for the transverse magnetic (TM) mode where the E field is polarized perpendicular to the plane of periodicity. The air holes in a dielectric region provide transverse electric (TE) mode where the H field is polarized perpendicular to the plane of periodicity.

Based on the value of vertical index contrast the structures can have, they are categorized into the following four geometries:

- Membrane holes: Hole-type PCs with a high vertical index contrast
- Membrane pillars: Pillar-based PCs with a high vertical index contrast
- Deeply etched holes: Hole-type PCs with a low vertical index contrast
- Deeply etched pillars: Pillar-based PCs with a low vertical index contrast

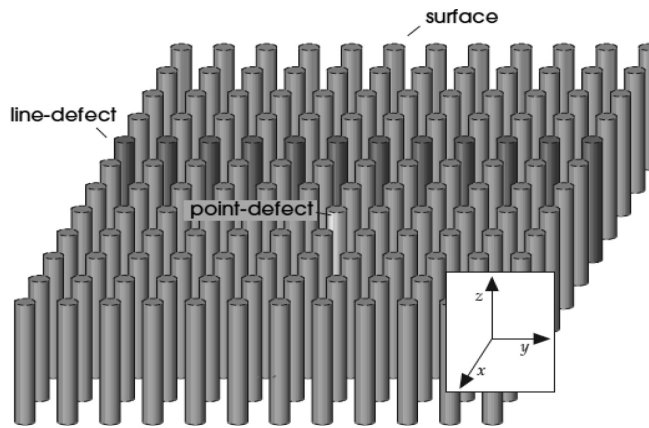
Furthermore, the membrane holes and pillars with high vertical index contrast received a crucial role for device realization.

10.2.1 PC Defects

In 2D PCs, bandgaps exist for in-plane propagation. Density of states is zero within the PBG as no modes are allowed here. By disturbing a single lattice location, a single localized mode or a set of closely lined up modes can be found that have frequencies lying in between the PBG. In 2D PCs, more options exist. As shown in [Figure 10.3](#), single column can be removed from the crystal or can be changed with the new one whose properties differ from the original such as size, shape, or dielectric constant (Prather et al. (2006); Jindal et al. (2016)).

Disturbing a single lattice site leads to a line defect in the z -direction. However, as propagation is considered only in the plane of periodicity and the disturbance is confined to a particular point in that plane only, this disturbance is considered as a point defect. Removing of one column will result into a peak that must be evanescent because it is not able to penetrate into the rest of the crystal as it has a frequency in the bandgap (Noda et al. 2002).

Disturbance in one column in the bulk of the crystal will allow a defect state to be localized in both x - and y -directions. This will induce point defect, depending on its size it would be called as microcavity if it is in the range of micrometer (Vučković et al. 2001)

**FIGURE 10.3**

Possible site demonstration of point, line, and surface defects in 2D PC. (From Joannopoulos, J.D. et al., *Photonic Crystal: Modeling of Flow of Light*, Princeton University Press, Princeton, NJ, 1995.)

and would be called as nanocavity if it is in nanometer range (Akahane et al. 2003). Perturbing one row in the bulk of the crystal is termed as line defects. Disturbance in entire row in PC lattice will create line defects known as photonic crystal waveguide (PCW) (Johnson et al. 1999). Finally, the surface defect is done by truncating the crystal at a surface which will allow a state to be localized in one direction (x).

10.3 PC Applications

The ability to control and manipulate the spontaneous emission is by introducing defects in PCs, and the related formation of defect state within PBG has been used for designing the optical devices for different applications that are directed toward the integration of photonic devices. 2D PCs are the choice of significant interest for both fundamental and applied researches, and also it finds its use in commercial applications. Figure 10.4 shows the summarized use of PCs in various applications.

The majority of PC applications use the phenomenon of PBG that opens the new road to design optical components in micrometer (μm) range. Waveguides that confine light through PBGs are a new development. Generally, the waveguide is intended to transport waves of a particular frequency from one place to another place through a curved path. The details of some of the applications of PCs are listed below.

Lasers: Laser is a device that is used to produce light signal, that is, incoming electrical signal is converted into light signal. The proper operation of spontaneous emission rate of lasers should be controlled as possible, which can be done using the cavity structure of PC as PBG helps to control spontaneous emission.

Multiplexer: Multiplexing is the generic term used to describe the operation of sending one or more signals over a single-fiber transmission line at different times or speeds, and as such, the device we use for this purpose is called a multiplexer (Cheng, et al. 2012).

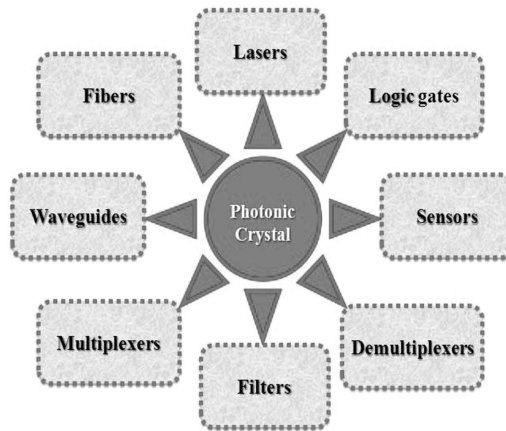


FIGURE 10.4
Different applications of photonic crystals.

Demultiplexer: A demultiplexer is a device that takes a single input line and routes it to one of several output lines. A single cavity in a PC will act as resonator, which is highly suitable for demultiplexer. Through PC-based demultiplexer, high quality factor with small mode volume can be realized.

Waveguide: A waveguide is generally used for the transportation of waves of a particular frequency from one place to another place along a path. Waveguides that confine light through PBG are a newer development.

Filters: A resonant filter can be realized using a nanocavity structure, which is used to remove and select a particular channel from the fiber optic system. Compared with the conventional filter, PC-based optical filter is highly attractive and selects a single or group wavelength. The photonic crystal ring resonator (PCRR) is used to design various filters such as bandpass and bandstop and add-drop filter.

Waveguide splitter: Waveguide splitter divides the power in an input waveguide equally between output waveguides. Using PC, it can be realized by the use of waveguides, that is, by missing air holes in a row if air in dielectric configurations is used or by missing dielectric holes if dielectric in air configuration is used (Frandsen et al. 2004).

Optical sensors: Optical sensor is a device that converts light rays into electronic signals. It measures the physical quantity of light and then translates it into a form that is readable by an instrument. An optical sensor is generally part of a larger system that integrates a source of light, a measuring device, and the optical sensor. PCs are an even more attractive for sensing due to their high sensitivity, high quality factor, low detection limit, high figure of merit (FOM), high linearity, and wide dynamic range (DR) (Zhang et al. 2015).

Photonic crystal fiber: Photonic crystal fiber (PCF) is a new class of optical fiber based on the properties of PCs. Because of its ability to confine light in hollow cores or with confinement characteristics, unlike the conventional optical fiber, PCF is now finding its applications in fiber-optic communications, fiber lasers, nonlinear devices, high power transmission, highly sensitive gas sensors, and other areas (Hoo et al. 2009).

Logic gates: PC logic gates are one of the important optical media that are highly attractive to create optical processors. Using the PC structures, the size of optical logic gates can be decreased to nanoscale. Also, these devices present the power consumption of about microwatts and response time less than a few picoseconds that lead to high switching speed (Salmanpour et al. 2015).

Circulators: Nonreciprocal optical devices, such as circulators or isolators, are important components in photonic integrated circuits as they have the special capability in guiding or isolating the reflection of electromagnetic waves. In the past few decades, circulator based on PCs has been extensively studied due to their ultracompact structures and excellent performances (Dehghanpour et al. 2014). Moreover, it is also investigated that almost of all kinds of optical devices could be realized through PCs.

10.4 PC-Based Sensor Overview

The development of photonic sensor, with specific reference to ultrasmall-compatible silicon-on-insulator (SOI) technology, allows improving sensing performance in terms of sensitivity, quality factor, limit of detection (LOD), and multiplexing capability. Optical sensors are the subject of intensive research over the recent years especially for the detection of various physical parameters such as pressure, temperature, voltage, current, electrical field, and biological and chemical agents. In this context, nanochip systems represent the state of the art of photonic sensing as they are expected to provide high stability, higher sensitivity, resistance to electromagnetic interference, and product improvements, such as smaller integration sizes and lower costs (Troia et al. 2013). Generally, PC shows a strong light confinement to a very small volume, enabling the detection of substances characterized by nanoscale range. In this section, we discuss a complete review on different PC sensor domains, PC sensor advantages, PC-based sensing mechanisms, PC-based sensing parameters, functional parameters of the sensor, PC-based sensor design platforms, and PC sensor applications.

10.4.1 PC Sensor Domain

PC sensing technology creates revolution in nanochip sensors. In general, sensor is a device that is used to detect the physical and chemical parameters. The sensors are collectively referred to as transducers, which serve the function of converting signal from one energy domain to another domain of interests. The domains are electrical domain (E), mechanical domain (M), chemical domain (C), radiation domain (R), magnetic domain (Ma), and thermal domain (T) (Liu 2011). PC-based sensors are used to detect all the six domains accurately. Figure 10.5 shows the PC sensing domains. Generally, the light signal passes through the sensing sample, and its corresponding output is observed by detecting the center peak wavelength shifted toward the higher wavelength. The different domain sensing parameters are listed below.

Electrical	Voltage, current, and electric field
Mechanical	Force, pressure, stress, strain, and speed
Chemical/Biosample	Glucose, pH, DNA, and blood sample
Radiation	Radiation, absorption, and transmission
Magnetic	Magnetic field
Thermal	Temperature

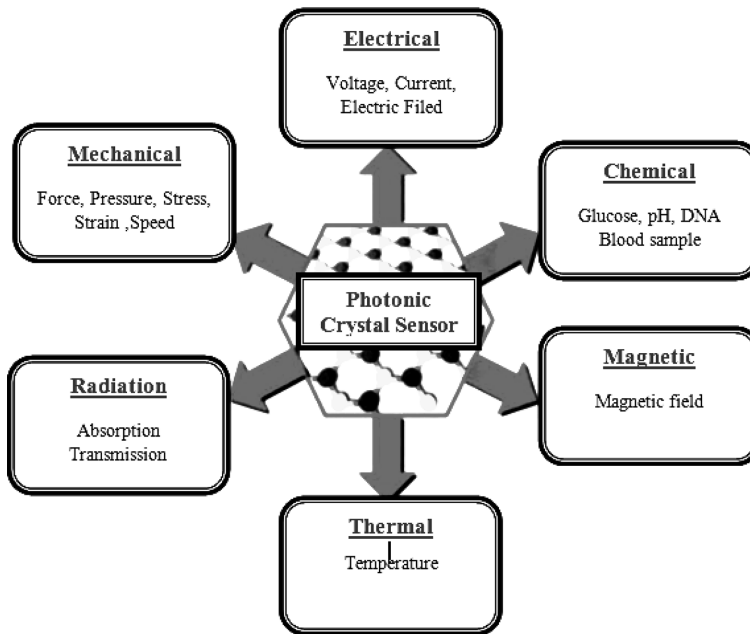


FIGURE 10.5
Photonic crystal sensing domain.

10.4.2 Functional Parameters of the Sensor

A number of static and dynamic factors must be considered in selecting a PC sensor to measure the desired physical parameters.

The PC-based sensor performance is generally evaluated by the following functional parameters:

- Quality factor (Q)
- Sensitivity (S)
- Resolution (R)
- Detection limit (D)
- FOM
- Transmission efficiency (η)
- DR

Quality factor: Quality factor (Q) is the widely used performance parameter for the measurement of light confinement in PC cavity. The three types of losses are mainly of primary concern: bending loss, leakage loss, and scattering loss. Generally, bending loss and leakage loss are very low, so they are eliminated within a structure. Scattering is caused by a physical surface roughness, produced at the time of fabrication. Thus, scattering loss is the primary loss, which is minimized to

achieve high Q factor. Numerically, the Q factor is defined as the ratio of resonant wavelength to change in the wavelength at full-width half-maximum (FWHM).

$$Q = \frac{\lambda_r}{\Delta\lambda}, \quad (10.1)$$

where λ_r is the resonant wavelength and $\Delta\lambda$ is the wavelength difference at FWHM. In an energy point of view, Q can be defined as follows:

$$Q = \frac{\text{Energy stored in cavity}}{\text{Energy loss in cavity}}. \quad (10.2)$$

Therefore, to achieve high Q factors, all the cavity losses need to be minimized (Kwon et al. 2008). The Q value calculation is shown in Figure 10.6.

Sensitivity: Typically, PC sensor is used to detect the refractive index change, which is measured using sensitivity. A refractive index sensor is filled with a liquid sample, with a resonant mode shift as shown in Figure 10.7a. If the sample refractive index is changed, the resonance condition of the device will also be changed, which leads to the shifting of resonant mode to a new wavelength. Numerically, the refractive index sensitivity (S) is calculated by the following equation:

$$S = \frac{\Delta\lambda}{\Delta n}, \quad (10.3)$$

where $\Delta\lambda$ represents the resonant wavelength difference and Δn represents the refractive index difference.

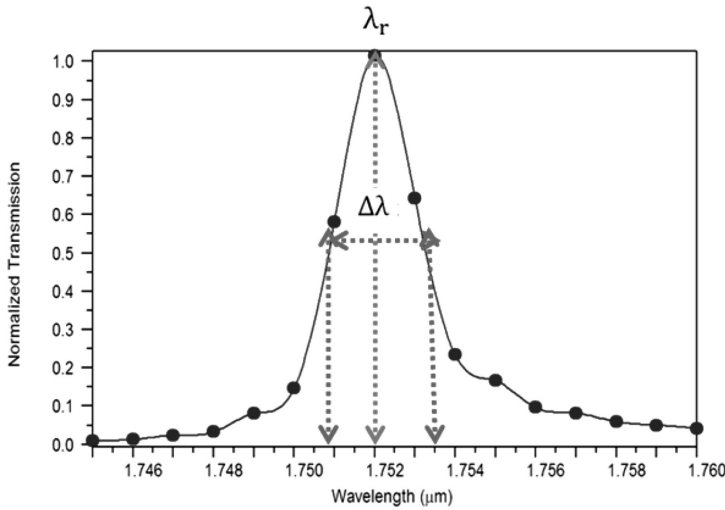


FIGURE 10.6
Schematic of quality factor calculation.

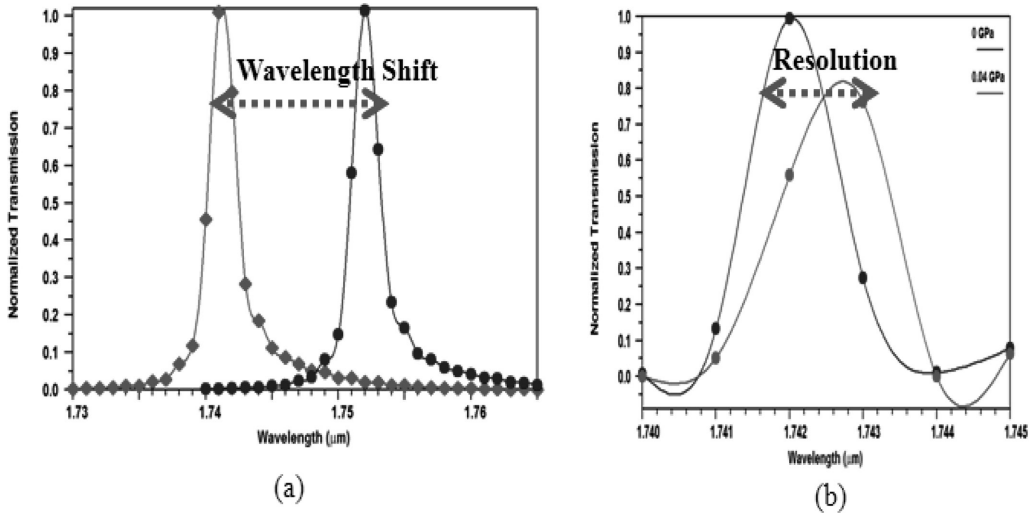


FIGURE 10.7

(a) Resonant wavelength shift due to sample refractive index changes and (b) smallest possible wavelength resolution.

Resolution: The sensitivity does not completely clear the capability of the device to detect and calculate the properties of the sample. Similarly, it is the ability to accurately measure the resonant wavelength shift that results from the sample. Therefore resolution characterizes the smallest possible spectral shift (PM wavelength shift) that can be accurately measured (White and Fan 2008).

Numerically, the resolution (R) is calculated by the following equation:

$$R = \Delta\lambda = \lambda_r - \lambda_s, \quad (10.4)$$

where λ_r is the resonant wavelength, λ_s is the smallest resonant wavelength shift, and $\Delta\lambda$ is the wavelength difference. The wavelength resolution is clearly shown in Figure 10.7b.

Detection limit: The sensitivity (S) and the wavelength resolution (R) combine to form the detection limit (D) of the sensor, which is given by the following equation:

$$D = \frac{R}{S}. \quad (10.5)$$

For refractive index sensing, the DL reports the smallest sample refractive index change that can be accurately measured (White and Fan 2008).

Figure of merit: The FOM of the sensor can be defined as the following equation:

$$\text{FOM} = \frac{S \times Q}{\lambda_r}. \quad (10.6)$$

The FOM value should be as high as possible, and it is a unitless parameter. To achieve high FOM, the resonant peak should be narrow and the resonant wavelength shift is very

high due to the detecting sample. From the equation, it is observed that the small resonant wavelength gives high FOM value (Wang et al. 2017).

Transmission efficiency: The transmission efficiency is one of the important parameters in photonic sensor, which is used to calculate the signal intensity level or output signal power. The transmission efficiency is calculated by the following equation:

$$p = \frac{p_0}{p_I}, \quad (10.7)$$

where P_0 is the output power at the resonance peak and P_I is the input power at the same wavelength. The transmission efficiency value should be high, that is, 100%, which is obtained by reducing the coupling loss between nanocavity and waveguide. In some cases (within resonator), transmission efficiency exceeds 100% due to constructive inference; in this situation, the optimum value of signal power is launched into PC waveguide to cavity.

Dynamic range: DR is the difference between the largest and smallest possible values of a detecting sample. The DR value should be high, which is obtained by a sensor designed with the single resonant mode instead of multiresonant mode. Moreover, all the cavity losses and the coupling loss between cavity and waveguide have been reduced.

10.5 “PC” Sensor Advantages

The main reasons that make PC technology for various parameter sensing can be abstracted as below (Zhang et al. 2015; Troia et al. 2013):

- Accuracy in results
- Ease of use
- Versatile
- Continuous monitoring available
- High Q factor
- High sensitivity
- Wider DR
- High linearity
- High selectivity
- Resistance to electromagnetic interference
- Smaller integration sizes
- Low cost
- Advanced fluidic handling capability
- Very low overall detection cost per measurement
- Reliable and portable
- Lower sample consumption

- Able to be fabricated with mass production
- Multiparameter analysis
- Ability to work under high temperature and high pressure conditions
- Enabling fast and real-time measurements.

10.6 Sensing Principle

10.6.1 Types of Sensing Modes

For an effective optical sensor, the various parameters affecting the sensor have been observed. In this section, two fundamental sensing principles commonly used in the photonic refractive index sensing are presented (Chao and Guo 2006) such as surface and homogeneous sensing.

10.6.1.1 Homogeneous Sensing

In homogeneous sensing, the device is typically surrounded with an analyte solution, which can be regarded as the top cladding of the waveguide. The homogeneously distributed analyte in the solution modifies the bulk refractive index of the solution. Such an index modification changes the effective index of the guided mode. In this mechanism, all materials including the detected analyte in the solution can contribute to the effective index shift, which leads to no specificity (Chao and Guo 2006). To solve this problem, surface sensing can be used. The homogeneous sensing mechanism is shown in [Figure 10.8a](#). In this case, the effective index of the propagating optical mode changes because of cover refractive index variations samples properly concentrated in the cover medium, where the photonic sensor is exposed.

10.6.1.2 Surface Sensing or Heterogeneous Sensing

The second scheme is surface sensing, that is, interfered by changing the position of a group of rods in a periodic structure or changing the shape of the particular rod. In surface sensing, the optical device is pretreated to have receptors or binding sites

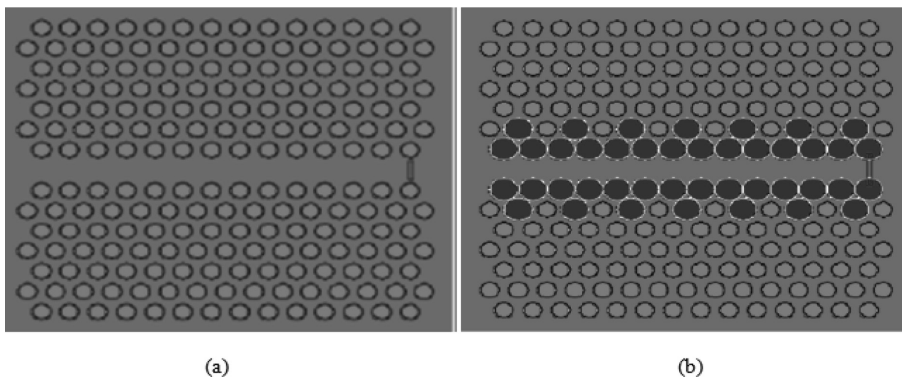


FIGURE 10.8

(a) Homogeneous sensing and (b) surface sensing.

on sensor surfaces, which can selectively bind the specific analyte. Accordingly, this method enables specificity and a label-free detection. Moreover, this method can provide a higher sensitivity due to the presence of a larger evanescent field at the waveguide boundary to probe the analytes (Chao and Guo 2006). In Figure 10.8b, the surface sensing principle is outlined. The surface sensing or heterogeneous sensing is created by selecting the particular inner hole; after that, the appropriate samples indicated by the dark color hole are filled in that particular area only, while the remaining hole is not filled. This method is highly sensitive compared with the homogenous sensing, due to which light strongly interacts with the filled sample (Bougriou et al. 2014). Moreover, the photon lifetime is high, which leads to enhance the sensitivity and selectivity of the detected sample.

10.7 Types of Detecting Mechanisms

There are two main detecting mechanisms, resonant wavelength shift and intensity variation, using which the calibration of the sensor can be done (Vos et al. 2007).

10.7.1 Intensity Variation Scheme

In intensity variation method, amount of change in the intensity at resonant wavelength at the output port is measured. In comparison with resonant wavelength shift method, the intensity variation method is more accurate, precise, and simple, which is because a steep slope observed at the output port will help in detecting the intensity change shown in Figure 10.9a. Only disadvantage of this scheme is the use of narrow range of wavelength shift, whereas the resonant wavelength shift method is used for the wider wavelength shift (Wen et al. 2016).

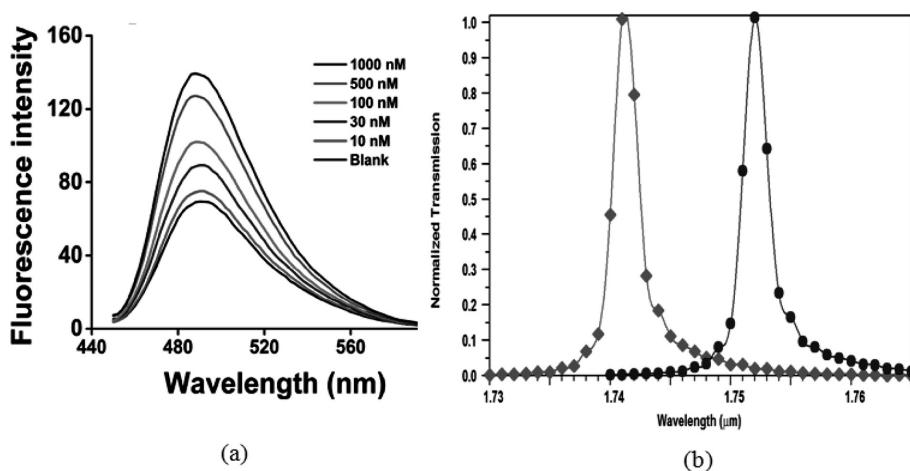


FIGURE 10.9

(a) Intensity variation and (b) resonant wavelength shift schemes. (Wen, Y. et al., *Sensors*, 16, 2155, 2016.)

10.7.2 Resonant Wavelength Shift Scheme

In resonant wavelength shift method, amount of change in the resonant wavelength is measured due to the presence of detecting sample, and it is clearly shown in [Figure 10.9b](#). The change in the resonant wavelength of optical sensor is due to change in the effective refractive index (ERI), which is the signature of presence of the sample. Accurate wavelength shift-based sensors can be improved by higher quality factor and measure a very minute change in ERI of cavity, a highly sensitive sensor is required (Vos et al. 2007).

10.8 Sensing Parameters

During the last decades, many optical sensors based on PC have been investigated and developed in a large range of sensing applications (Zhang et al. 2015; Troia et al. 2013), which are given below:

- Temperature
- Pressure
- Displacement
- Force
- Magnetic fields
- Chemical species
- Strain
- Voltage
- Cancer cell
- Glucose
- Sugar and salt
- Salinity level in sea water
- Chemical concentrations
- Blood components
- Urine and blood glucose level
- Bacteria
- Virus
- Protein concentration
- Electric fields

10.9 Numerical Methods

Many methods are available to analyze the dispersion behavior and transmission spectra of PCs such as transfer matrix method (TMM) (Pendry and MacKinnon 1992), finite difference time domain (FDTD) method (Taflove 2005), plane wave expansion

(PWE) method (Pendry 1996), and finite element method (FEM) (Pelosi et al. 1997). Each method has its own merits and demerits. Among these, PWE and FDTD are the widely used methods with respect to their performance, and they are also meeting the demands required to analyze the PC-based optical devices. The PWE method is initially used for theoretical analysis of PC structures, which makes use of the fact that eigenmodes in periodic structures can be expressed as a superposition of a set of plane waves. Although this method can obtain an accurate solution for the dispersion properties (propagation modes and PBG) of a PC structure, it still has some limitations, that is, transmission spectra, field distribution, and back reflections cannot be extracted as it considers only propagating modes. An alternative approach that has been widely adopted to calculate both transmission spectra and field distribution is based on the numerical solutions of Maxwell's equations using the FDTD method. Typically, the PWE method is used to calculate the PBG and propagation modes of the PC structure, and FDTD is used to calculate the spectrum of the power transmission. The PWE and FDTD methods are highly attractive for designing the different sensors due to their following features.

Features of PWE Method (Hsue and Yang 2003):

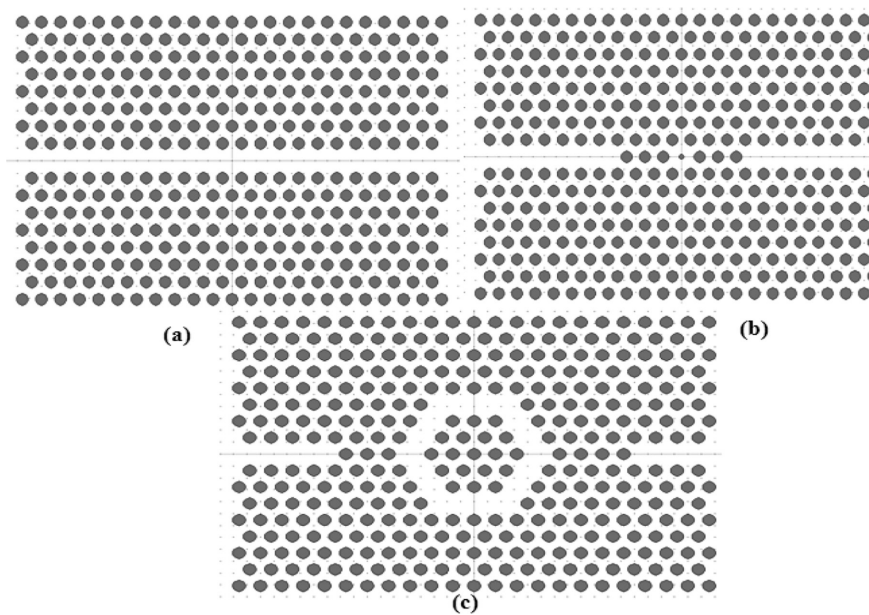
- Both the “air rods in dielectric” and “dielectric rods in air” problems can be solved, without any restriction on the shapes of the rods.
- All information getting from the complete set of the eigenfunctions of the translation operator are used, including both the propagating and evanescent modes, which makes it easy to analyze the PC.
- It can accurately calculate the transmittance and reflectance for a very thick PC sample.

Features of FDTD Method (Yee 1966):

- From the mathematical point of view, it is a direct implementation of Maxwell's curl equations.
- Broadband frequency response can be easily predicted as the analysis is carried out in the time domain.
- Arbitrary, irregular geometries, size of any size can be easily modeled.
- It is capable of analyzing structures having different types of materials.

10.10 “PC”-Based Sensor Design Platforms

Generally, the PC-based optical device realized by introducing line defects and point defects. The line defects introduce to design the waveguide structure and point defect introduces to design the nanocavity structure. Both line defect and point defect introduce to design nanoring resonator structure. The multinano cavities are combined to make cascade cavity structure. [Figure 10.10](#) shows the different PC-based sensor design platforms.

**FIGURE 10.10**

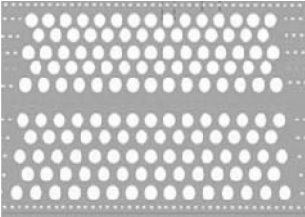
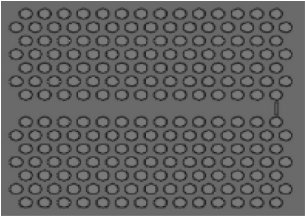
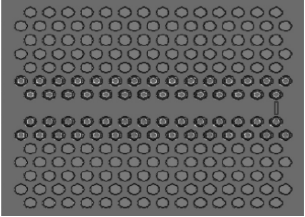
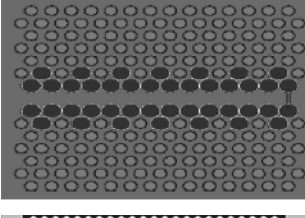
Schematic structures of (a) PC waveguide, (b) PC cavity, and (c) PC ring resonator.

10.10.1 PC Waveguide-Based Sensing

A PC waveguide-based sensor can be created by inducing the line defect in perfect PC. As it provides lossless platform and its used in many applications such as directional coupler and sensor. The PCW allows the propagation of a small range of wavelengths that lie within the range of PBG. The transmission in the PCW depends entirely on the ERI of PC slab. Compared with the conventional waveguide, PCW structure strongly controls the light signal and strongly interacts the light with sensing sample based on the slight light effect. Bougriou et al. (2012) have proposed a PCW-based chemical sensor structure for the detection of deionized water and it has been observed that a 270 nm wavelength position of the upper band edge shift was observed corresponding to a sensitivity of more than 818 nm per refractive index unit. Kumar et al. (2015) have proposed a PC-based bi-periodic waveguide structure designed to detect both gas and fluid where an array of super cavity is used to pass the resonance wavelength through the waveguide. For gas-sensing application, the sensitivity of the sensor has been found to be 610 nm/RIU with a minimum detection limit of 0.0001 RIU. Table 10.1 gives the comparison of various reported PC waveguide structures. Recently, many PC-based waveguides are proposed and designed for various applications due to low group velocity and low dispersion and very less leakage of light (Krauss 2017); however, it provides less sensitivity. Further, the waveguide structure is modified by inserting annular ring-based defect holes or holes inserted within the waveguide region, which enhanced the sensitivity due to annular ring dominant for both TE and TM modes (Kurt and Citrin 2005). However, the detection limit is very high and the quality factor is very low, which overcomes using a biperiodic waveguide structure (Kumar et al. 2015). This structure is designed by the radius of adjacent hole changed only to form an array of super cavities, which provide good-quality factor and low detection

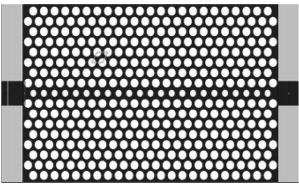
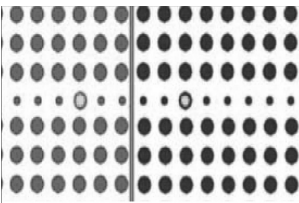
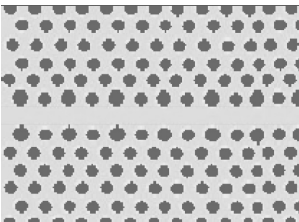
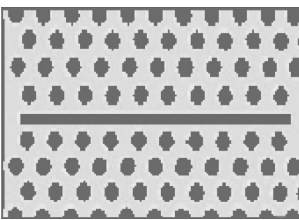
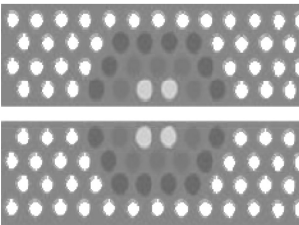
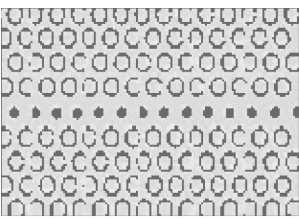
limit. However, in all the aforementioned PCW structures, light is confined in high refractive index material where the light–sample interaction is not sufficient (Aghababaeian et al. 2011), which can be enhanced by confining light in a low refractive index material. This is accomplished by introducing an air slot within a PCW structure, which has high potential for sensing applications; this type of structure has very good detection limit; still it is not widely used due to very low fabrication tolerance (Goyal et al. 2017).

TABLE 10.1
Comparison of Various Reported PC Waveguide Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	***	***	0.003	Protein concentrations	Skivesen et al. (2007)
	66.73	***	***	Voltage	Yang et al. (2011b)
	***	636	***	Deionized water	Bougriou et al. (2013)
	***	927	***	Deionized water	Bougriou et al. (2013)
	***	55	***	1.0–1.2	Goyal and Pal (2015a)

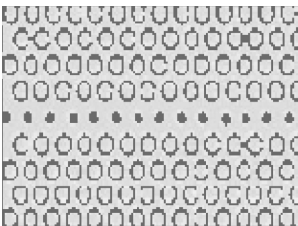
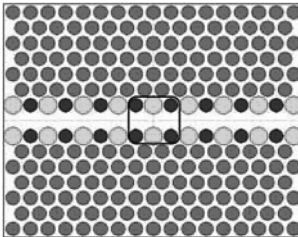
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TABLE 10.1 (Continued)
Comparison of Various Reported PC Waveguide Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	***	386	***	1.0–1.5	Goyal and Pal (2015a)
	180	***	***	Displacement	Olyae and Azizi (2014)
	***	181	***	Acetylene	Zakrzewski and Patela (2017)
	***	***	***	CO, CO ₂ , H ₂ S	Zhang et al. (2013)
	7500	370	2.3 × 10 ⁻⁵	Hexane, Acetone Sensing	Mirsadeghi et al. (2013)
	***	513	0.0001	N ₂ , H ₂ , NH ₃ , O ₂	Goyal and Pal (2015b)

(Continued)

TABLE 10.1 (Continued)
Comparison of Various Reported PC Waveguide Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	***	606	0.0001	1.00–1.50	Benelarbi et al. (2016)
	***	610	0.0001	Gas and fluid	Kumar et al. (2015)

All the above-discussed PCW structure operating principles are based on the ERI, and the operating mechanism is based on the label-free binding molecule sensing, which is done by the strong interaction between photon and sensing sample. The PCW has some advantages and disadvantages (Goyal et al. 2017).

Advantages:

- Loss is very low
- High sensitivity
- High transmission efficiency

Disadvantages:

- Very low quality factor
- Crosstalk is very high
- Light–sample interaction is very low
- High mode volume
- Large number of analysis requires for sensing
- Large sensing area requires very minute amount of target analyses.

All the aforementioned issues are overcome by PC waveguide-coupled cavity structure.

10.10.2 PC Cavity-Based Sensing

Combination of waveguide and nanocavity is realized by creating line and point defects in PC used as a sensor, providing high quality factor, high sensitivity, low detection limit, and low cross talk (Goyal et al. 2017).

The different types of 2D PC cavities such as simple PC cavity, line-coupled PC cavity, shoulder-coupled PC cavity, and hetero PC cavity are shown in Figure 10.11a–d.

Figure 10.11a shows the basic types of PC cavity, formed by introducing a single point defect in the periodic PC structure. As a result of the defect, the periodicity of the PC is broken. For suitable defect size and arrangement, localized modes can take place, which have wavelength within the bandgap. PC line defect cavity (L_n cavity) is an optimization of a point defect cavity, as shown in Figure 10.11b, where “ n ” numbers of point defects are introduced. In most applications, this type of cavities is coupled perpendicularly by shining light on top. This cavity possesses low-quality factor than the point defect PC cavity. Figure 10.11c shows in-line coupling (shoulder coupling) concepts; the light coupling between PC cavity and waveguide structure is used to improve the mode volume and provides high quality factor; however, it distorts their regularity of the point defect cavity due to resonance splitting. Finally, Figure 10.11d shows PC heterostructure cavity, which is designed by varying a lattice hole diameter and forming two PC structures PC_1 and PC_2 . The PC_2 acts as cavity, whereas PC_1 is used as a mirror for the designed PC cavity structure. This structure exhibits strong confinement of a light in the defect area and has long photon lifetime, leading to high quality factor and high sensitivity. Table 10.2 shows the comparison of various reported PC cavity-coupled waveguide structures.

Table 10.2 lists the comparison of various reported simple PC cavity structures. From the table, it is observed that this type of structure is used to sense the various parameters and provides the maximum quality factor. The sensitivity and minimum detection limit are 2.02×10^5 and 1571 nm/RIU, respectively.

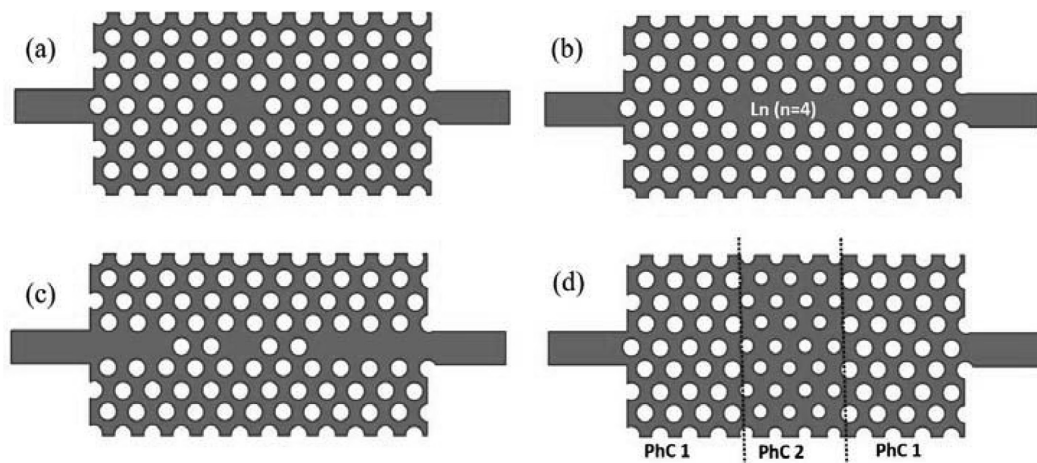


FIGURE 10.11

Schematic of PC cavity structure. (a) Simple PC cavity, (b) L_n PC cavity, (c) shoulder-coupled PC cavity, and (d) heterostructure PC cavity. (From Goyal, A.K. et al., *J. Phys. D Appl. Phys.*, 50, 1–24, 2017)

TABLE 10.2
Comparison of Various Reported Simple PC Cavity Structures

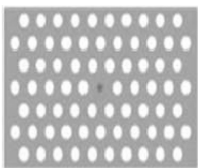
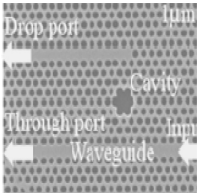
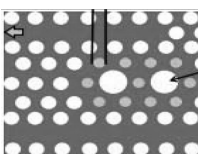
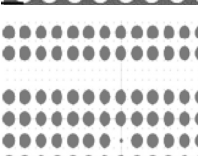
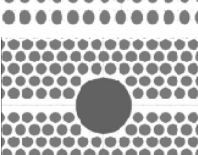
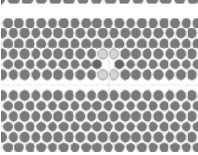
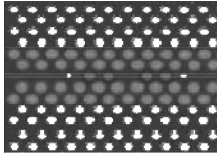
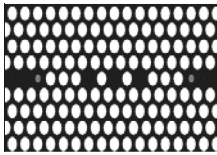
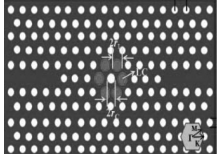
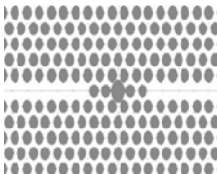
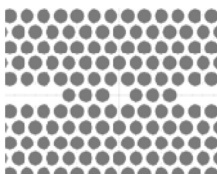
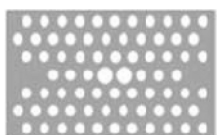
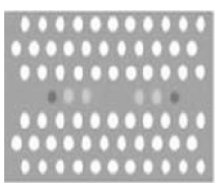
Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	400	200	0.002	1.446–1.454	Chow et al. (2004)
	10 ⁵	1570	0.00014	Sucrose concentration	Sana et al. (2016)
	***	180	0.001	Voltage	Yang et al. (2011a)
	3000	83.75	***	DNA	Mohsenirad et al. (2016)
	2.02 × 10 ⁵	1571	4.15 × 10 ⁻⁶	Sucrose concentration	Sana et al. (2017)
	1470	***	***	Pressure	Olyae and Dehghani (2012)
	***	***	***	Water temperature	Nikoufard et al. (2016)
	***	***	***	Force	Stomeo et al. (2007)

Table 10.3 presents the comparison of various reported shoulder-coupled PC cavity structures. From the table, it is investigated that the shoulder-coupled cavity is worked as a versatile platform, that is, it senses the various parameters, and the maximum quality factor, sensitivity, and the minimum detection limit are 11477.3, 500 nm/RIU, and 3.79×10^{-6} , respectively.

TABLE 10.3
Comparison of Various Reported Shoulder-Coupled PC Cavity Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/ RI Range	References
	1105	450	***	Methane sensing	Qian et al. (2016)
	32000	400	1×10^{-4}	1.00–1.20	Goyal et al. (2016)
	9050	300	0.002	Electric field	Zhao et al. (2017)
	15000	141.67	0.0006	Temperature	Najaf Gholinezhad and Olyaei (2014)
	1.47×10^4	425	0.001	Biochemicals	Harhouz and Hocini (2015)
	17890	500	0.0001	1.0–1.6	Shiramin et al. (2013)
	2966	131.7	3.79×10^{-6}	Sugar concentration	Zhou et al. (2014)

(Continued)

TABLE 10.3 (Continued)

Comparison of Various Reported Shoulder-Coupled PC Cavity Structures

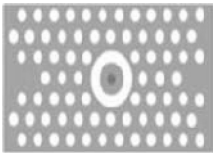
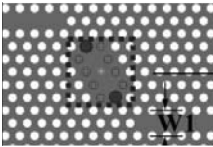
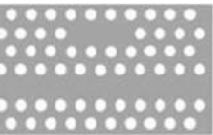
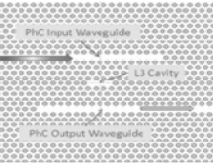
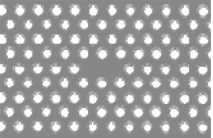
Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	11477.3	160	8.75×10^{-5}	Deuterium water and glycerol solution	Huang et al. (2015)
	7602	***	***	Magnetic field	Su et al. (2016)

Table 10.4 lists the comparison of various reported line PC cavity and heterostructure PC cavity structures. From the table, it is observed that these type of structures are used to assess the various parameters. The maximum quality factor, sensitivity, and the minimum detection limit of the line defect-based PC structure are 4459, 388 nm/RIU, and 0.006 RIU⁻¹, respectively. The maximum quality factor, sensitivity, and the minimum detection limit of heterostructure-based PC cavity are 2.6×10^4 , 510 nm/RIU, and 1.25×10^{-5} , respectively.

All the above-discussed PCC structure operating principle is based on the ERI and operating mechanism based on the label-free binding molecule sensing, which is done by the strong interaction between photon and sensing sample. The PC cavity has some advantages and disadvantages (Goyal et al. 2017; Falco 2009).

TABLE 10.4

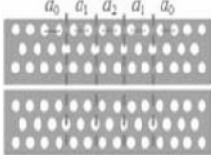
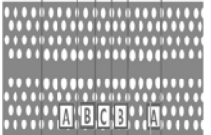
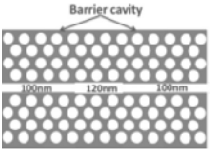
Comparison of Various Reported Line PC Cavity and Heterostructure PC Cavity Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	3000	63	0.006	Water and isopropanol	Dorfner et al. (2008)
	33,000	3000	0.0008	Gas	Awad et al. (2010)
	69,000	***	***	Acetylene, hydrogen-cyanide	Liapis et al. (2016)

(Continued)

TABLE 10.4 (Continued)

Comparison of Various Reported Line PC Cavity and Heterostructure PC Cavity Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	25,000	235	1.25×10^{-5}	Cargille liquid	Caer et al. (2014)
	40,000	80	1×10^{-4}	N ₂ , SF ₆	Sunner et al. (2008)
	2.6×10^4	510	1×10^{-5}	He, N ₂ , CO ₂	Zhang et al. (2010)

Advantages:

- High sensitivity
- Low detection limit
- Very high quality factor
- Light and sample interaction are very high
- Low mode volume
- Small amount of analysis requires for sensing
- Strong confinement of light within cavity
- Long photon lifetime within cavity
- Small sensing area requires very minute amount of target analytes
- Easily integrated with photonic circuits
- Easy to demodulate
- Flexible in structural design
- Easy to sense multiparameters

Disadvantages:

- Very low fabrication tolerance
- Temperature and humidity affect performance of the device
- Large coupling loss

10.10.3 PC Ring Resonator-Based Sensing

To convert the amount of sample to a detectable signal of a nanoring sensor, PCRR is formed by two waveguides, among them one should be in a ring shaped that generally interacts with each other at particular points and may be horizontally or vertically at some wavelengths. So far, PCRR structure is used to design many sensors for different applications, which provide long interaction between light and analyte occurred within nanoresonator, and hence small amount of sample is sufficient for detection. In the literature, the pressure sensor using the PC was reported periodically. Arunkumar et al. (2017) reported a pressure sensing based on 2D elliptical PCRR structure and achieved a linear resonant wavelength shift according to the applied pressure from 1 to 10 GPa. The sensing platform consists of inline quasi waveguide and elliptical ring resonator, which is shown in Figure 10.12a. The change in the resonant wavelength and transmission efficiency in the sensor are occurred due to the change in refractive index for different values of pressure as

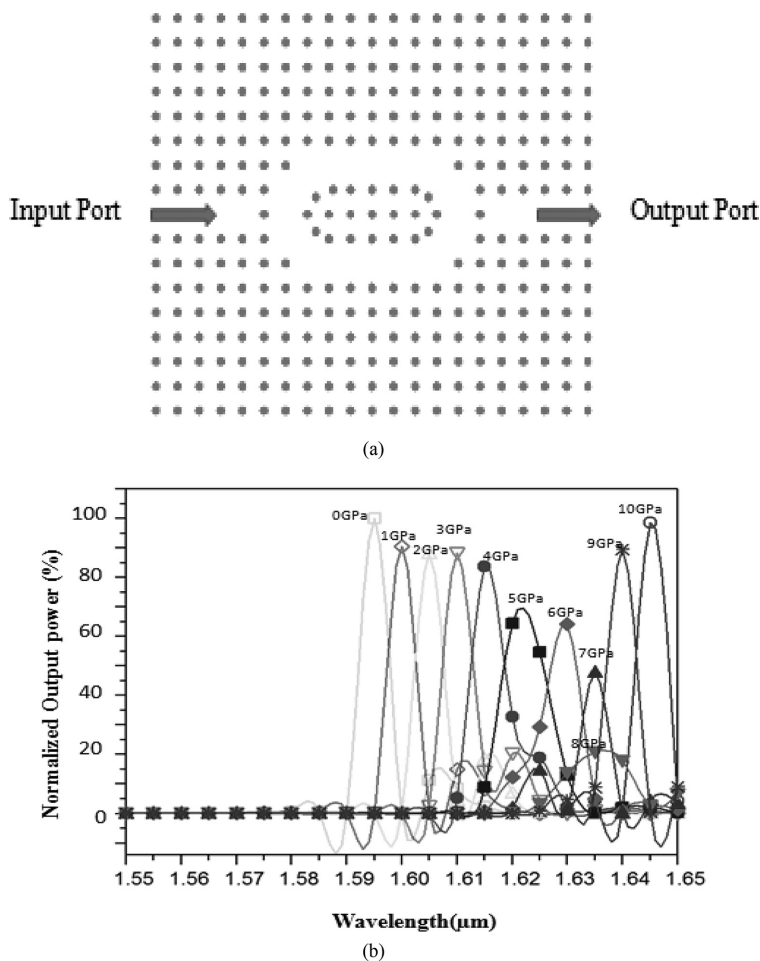


FIGURE 10.12

(a) Schematic diagram of PCRR based pressure sensor and (b) normalized transmission spectra of the sensor. (From Arunkumar, R. et al., *Photon. Opt. Techn.*, 3, 30–33, 2017.)

shown in Figure 10.12b. The maximum Q factor and output power are 330.8% and 100%, respectively. The sensitivity and DR of the proposed sensor are 1 and 10 GPa, respectively.

In recent years, many PC structure-based force sensors were designed theoretically and experimentally. Suganya and Robinson introduced a 2D PC based on the force sensor using a parallelloid ring resonator for sensing the force (Suganya and Robinson 2017b). An elasto-optic effect method is used to analyze the forces that persist over PC. The basic structure of the force sensor is shown in Figure 10.13a. The structure consists of parallelloid PCRR, nanocavity, reflector, and waveguides. The resonant wavelength intensity is reduced from 100% to 15% when the force is applied from 0 to 130 μN , and its normalized output is shown in Figure 10.13b. The FDTD simulation results show that the maximum quality factor and output power of the sensor are 145.5% and 100%, respectively.

Radhouene et al. (2017) reported a high-sensitive and high quality factor superellipse using a PCRR-based temperature sensor. The designed sensor had a linear behavior between 0°C and 67.4°C of the applied temperature and the temperature sensitivity of 65.3°C . The temperature sensing platform and its output spectrum are shown in Figure 10.14a and b, respectively.

Table 10.5 lists the comparison of various reported PCRR-based structures. From the table, it is noted that these structures are used to sense the physical, chemical, and biological parameters. Moreover, circular, rhombic, and hexagonal structure-based ring resonators are highly attractive for different sensing applications and also provide better results. The high transmission efficiency of 100% is achieved by a circular ring resonator; however, the quality factor and refractive index sensitivity are very low, which are overcome by a rhombic ring resonator that provides high refractive sensitivity of 1000 nm/RIU and 100% transmission efficiency; however, the quality factor is very low. These issues are mitigated by a hexagonal ring resonator that provides a high quality factor of 35,517 and a low detection limit of 1.24×10^{-5} with good sensitivity.

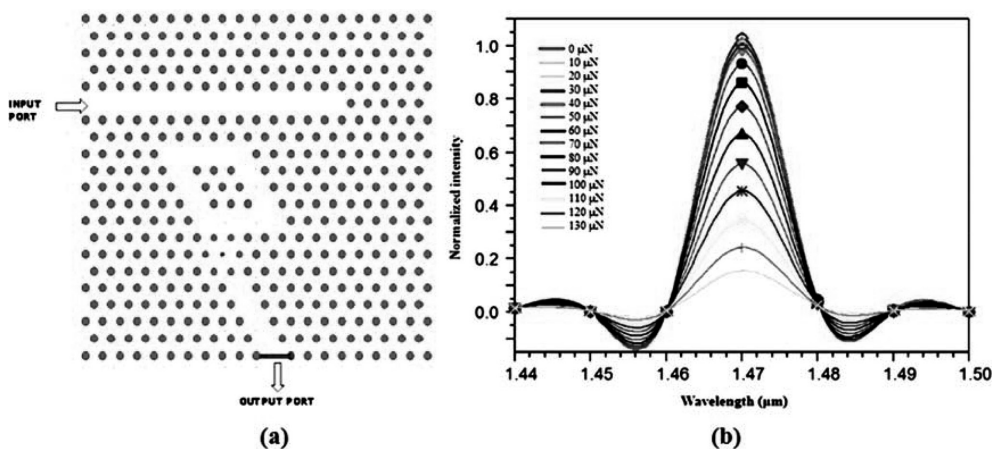


FIGURE 10.13

(a) Schematic of force sensor and (b) normalized transmission spectrum of the sensor of force (0–130 μm). (Suganya and Robinson 2017b.)

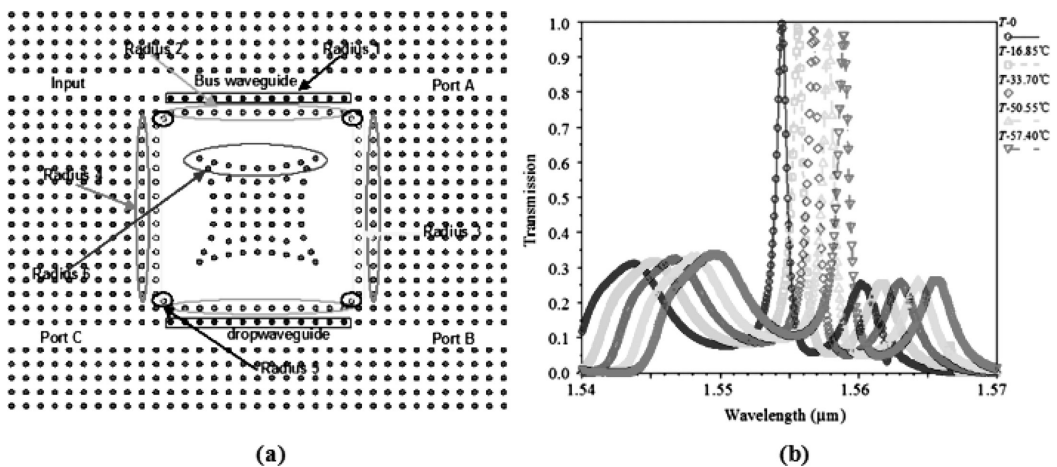
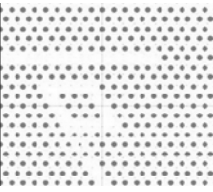
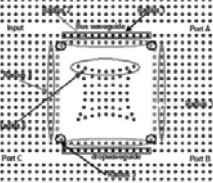


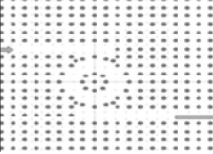
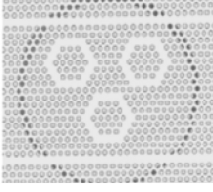
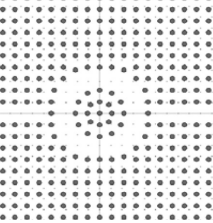
FIGURE 10.14 (a) Schematic of PCRR-based temperature sensor and (b) output at port C at different temperatures. (Radhouene, M. et al., *Photonic Sens.*, 7, 1–6, 2017.)

TABLE 10.5
Comparison of Various Reported PCRR-Based Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	340	***	***	Pressure	Arunkumar et al. (2017)
	145	***	***	Force	Suganya and Robinson (2017)
	1727	***	***	Temperature	Radhouene et al. (2017)

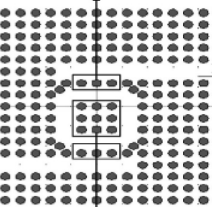
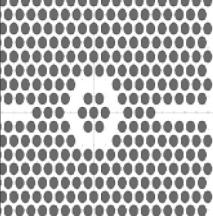
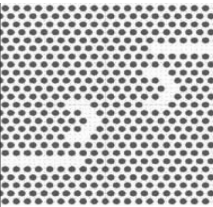
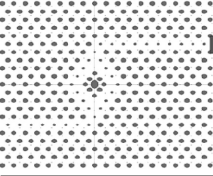
(Continued)

TABLE 10.5 (Continued)
Comparison of Various Reported PCRR-Based Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	***	***	***	Temperature	Mallika et al. (2015)
	104	***	***	Temperature	Robinson et al. (2015a)
	5522	***	***	Force	Mai et al. (2010)
	1737	***	***	Force and pressure	Li and Lee (2011)
	16,000	***	***	Force	Sreenivasulu et al. (2018)
	455	***	***	Glucose concentration	Robinson et al. (2015b)

(Continued)

TABLE 10.5 (Continued)
Comparison of Various Reported PCRR-Based Structures

Schematic Design	Quality Factor	Sensitivity nm/RIU	Detection Limit (RIU ⁻¹)	Sensing Parameters/RI Range	References
	***	***	***	1.33–1.47	Chen et al. (2014)
	1750	4.125	***	1.33–1.51	Olyaei and Mohebzadeh-Bahabady (2014)
	35,517	330	1.24×10^{-5}	Deuterium water and glycerol solution	Huang et al. (2014)
	2700	***	***	1.33–1.48	Olyaei and Mohebzadeh-Bahabady (2014)
	178.5	1000	0.006	Glucose concentration	Suganya and Robinson (2017)

The operating principle of all the above-discussed PCRR structures is based on the ERI and operating mechanism based on the label-free binding molecule sensing, which is done by the strong interaction between photon and sensing sample. The PCRR structure has some following advantages and disadvantages.

Advantages:

- High sensitivity
- Low detection limit

- Very high quality factor
- Light and sample interaction are very high
- Small amount of analytes requires for sensing
- Long photon lifetime with in cavity
- Small sensing area requires very minute amount of target analytes
- Flexible in structural design
- Very low crosstalk
- High transmission efficiency

Disadvantages:

- Very low fabrication tolerance
- Temperature and humidity affect the performance of the device
- Small bending loss

10.11 “PC” Sensor Applications

Typically, 2D PC is used for biomedical applications and for sensing many real-time parameters in a remarkable way (Ahmmed et al. 2017). The possible applications of PCs are shown in [Figure 10.15](#).

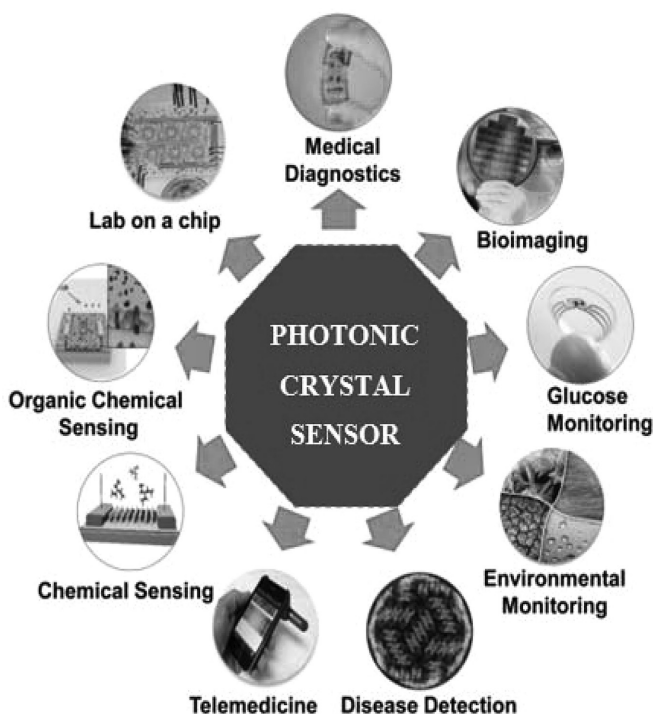


FIGURE 10.15

Different applications of PC-based optical sensor. (From Ahmmed A. et al., *Sens. Actuators B Chem.*, 243, 311–325, 2017.)

10.12 “PC”-Based Biosensor: Overview

After the invention of optical sensor by Clark and Lyons in 1962, optical sensing mechanisms receive considerable attention in industrial process control, military, environmental monitoring, medical diagnostic, and so on. Recently, fiber optic sensors have received keen attention due to their unique properties such as resistance to electromagnetic interference, high sensitivity, small sensing unit, safety in hazards or explosive environments, the possibility of processing the signal at large distances, the ability to work under high temperature, high voltage, and high pressure conditions (Zhao et al. 2000).

10.12.1 Biosensor

A biosensor is a device that makes use of a biological detection system. Biosensing is the process of using biosensors to gather information about living systems. The precise interpretation of the term “biosensing” depends on the research domain. Biosensing can be understood as a sensing process that incorporates biological material or reactions into a sensor, to improve an existing system, add new features, or create a completely new sensor—even one that might not exist as such in existing living systems. With this in mind, one could define a biosensor as a self-contained integrated device consisting of a biological recognition element such as enzyme, antibody, DNA, or microorganism, which is interfaced to an analytical device and together respond in a concentration-dependent manner to a given analyte. The major elements of a biosensor are shown in [Figure 10.16](#). The definition of a chemical biosensor in 2001 is often quoted in biosensor research: “An electrochemical biosensor is a self-contained integrated device, which is capable of providing specific quantitative or semi-quantitative analytical information using a biological recognition element which is retained in direct spatial contact with an electrochemical transduction element” (Long et al. 2013).

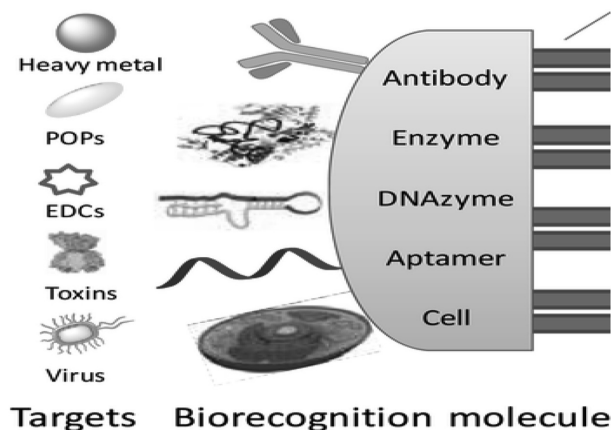


FIGURE 10.16
Major elements of a biosensor.

10.12.2 Types of Biosensors

Biosensors can be classified by their biotransducer type. The most common types of biotransducers used in biosensors are as follows:

- Calorimetric biosensor
- Potentiometric biosensor
- Amperometric biosensor
- Optical biosensor

10.12.3 Optical Biosensor

Optical techniques have always been used for a large number of metrological and sensing applications. Optical sensor is an analytical device used to convert the amount of analytes into a detectable signal. It depends upon a phenomenon called the evanescent field to monitor changes in refractive index occurring within a few hundred nanometers of the sensor surface. Over the past three decades, there is a vast need for the development of easy-use, sensitive, and inexpensive sensors for detection and identification of substances. Sensing platforms such as fiber Bragg grating (FBG) (Shu et al. 2001) and surface plasma resonance (Zhao et al. 2009) have been used.

In optical sensors, one of the most direct ways to sense the optical properties is to identify the refractive index change due to the analytes. Recently, PCs become an attractive sensing platform because they provide strong light confinement. Unlike many sensing platforms that utilize the interaction between the small evanescent tail of the electromagnetic field and the analyte, PCs can be designed to localize the electric field in the low refractive index region, which makes the sensors highly sensitive to a small refractive index change produced by substance immobilization on the pore walls (Liu and Salemk 2012). However, the advances in the development of high quality and competitive optoelectronic devices and sensors have largely contributed to the expansion of PC technology for sensing as well.

10.12.4 PC-Based Biosensor Principle of Operation

The PC-based biosensor system is composed of optical source, PC-based sensor, photo detector, signal processing unit, and display. Figure 10.17 shows the schematic of PC-based optical sensing.

Optical source: A wide selection of light sources is available for optical sensor applications, which include highly coherent gas and semiconductor diode lasers; broad spectral band incandescent lamps; and narrow-band, solid-state, light-emitting diodes. The important requirement of a light source is obviously good stability.

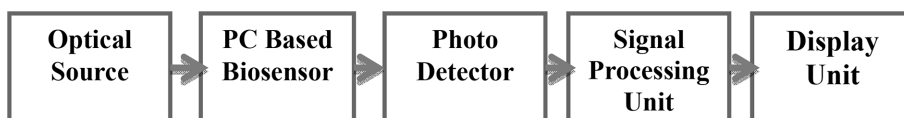


FIGURE 10.17

Schematic of PC-based optical sensing.

In certain applications such as portable instrumentation, LEDs have significant advantages over other light sources because they are small and inexpensive, consume lower power, produce selective wavelengths, and are easy to work with.

PC-based sensor: Various optical elements are used routinely to manipulate light in optical instrumentation, which include lenses, mirrors, light choppers, beam splitters, and couplers for directing the light from the light source into the optic sensor or a specific area on a waveguide surface and collecting the light from the sensor before it is processed by the photodetector. For wavelength selection, optical filters, prisms, and diffraction gratings are the most common components used to provide a narrow bandwidth of excitation when a broad width light source is used.

Photodetectors: A number of factors must be considered for choosing photodetectors for optical sensors, which include sensitivity, directivity, noise, spectral response, and response time. Typically, two photodetectors are used in optical instrumentation because it is often necessary to include a separate reference detector to track fluctuations in source intensity and temperature. By taking a ratio between the two detector readings, whereby a part of the light that is not affected by the measurement variable is used for correcting any optical variations in the measurement system, and thereby a more accurate and stable measurement can be obtained.

Signal processing unit: Typically, the signal obtained from a photodetector provides voltage or current proportional to the measured light intensity. Usually, the output from a photodetector is connected directly to a preamplifier before it is applied to sampling and analog-to-digital conversion circuitry residing inside a computer. More often, two different wavelengths of light are used to perform a specific measurement. One wavelength is usually sensitive to changes in the species being measured, and the other wavelength is unaffected by changes in the analyte concentration.

Display: The output signal is processed by a signal processing unit and then the same will be displayed, which is in readable form.

10.12.5 PC-Based Biosensor Advantages

The main reasons that make PC technology for biosensing are abstracted as follows:

- High quality factor
- High sensitivity
- Wider DR
- High linearity
- High selectivity
- Advanced fluidic handling capability
- Very small amount of sample consumption
- Multiparameter analysis
- Accuracy in results
- Minute detection capability
- Ease of use
- Versatile

10.12.6 PC-Based Different Biosensing Analytes

During the last decades, many optical biosensors based on PC have been investigated and developed for a wide range of medical applications.

PC-Based Biosensor Sensing Analytes:

- Glucose
- Sucrose concentration
- Urine albumin
- Urine urea
- Urine bilirubin
- Water temperature
- Salt concentration
- Sugar concentration
- Salinity level in drinking water
- Biochemical concentrations
- Cell components
- Blood components
- Urine and blood glucose level
- *Escherichia coli*
- Pathogens
- Virus
- DNA molecule
- Salt and glucose
- Detection of glycosuria
- Hemoglobin
- Glycated hemoglobin

10.13 “PC”-Based Biochemical Sensor

10.13.1 PCRR-Based Salinity Sensor

Robinson and Nakkeeran (2012) proposed and designed a nanosensor for sensing the salinity of seawater using 2D PC-based circular ring resonator. The geometry of this sensor is square lattice with configuration of dielectric rod in air host. The PC ring resonator coupled to inline quasi waveguide is the proposed design of sensor. The waveguide is configured by removing some silicon rods in input and output sides, and the circular PCRR is formed by changing the position (25%) of the inner rods. The proposed sensor operating wavelengths range from 1580 to 1590 nm. For salinity measurement, the refractive index of the seawater is considered, which alters the refractive index of the sensor that in turn changes the output power. By measuring the

output power, it is possible to assess the presence of salinity and to quantify the level of salinity in seawater at a chosen temperature.

The simulation results show that the quality factor and output power of the sensor are 477.83% and 99.5%, respectively. Furthermore, the PCRR structure optimized with one-one coupling rod is selected with high Q-factor and thereby high transmission efficiency is achieved. The normalized spectrum results show that there is 2.69% output power reduction for every 5% increase in salinity, which is highly sufficient for measuring the salinity of seawater. The minimum detectable (sensitivity) and DR of the proposed salinity sensor is 1% (1 g/L) and 100%, whereas for temperature, it is 5°C and 25°C, respectively. Figure 10.18a and b shows the circular PCRR-based sensor design and normalized output spectrum at different salinity levels, respectively.

10.13.2 PCRR-Based Glucose Sensor

Suganya and Robinson (2017a) presented 2D PC-based biochemical sensor using a rhombic ring resonator for monitoring the glucose concentrations. The sensor is designed to monitor the glucose level from 0 to 330 g/L. The proposed sensing platform is based on a triangular lattice with silicon rods arranged in air background. The sensor structure is composed of rhombic ring resonator and two waveguides. Bi-periodicity and rhombic ring resonator are the center of the sensor and play an important role in detecting different glucose concentrations. The working principle of the sensor is the ERI. The glucose concentration is varied there is moderate shift in the resonance wavelength. The PCRR-based biochemical sensor has to be designed in such a way. The optical characteristic of the sensor is analyzed by FDTD method. The sensor is designed in the wavelength range of 1540–1560nm. The sensitivity, quality factor, and output power of the sensor are 1000 nm/RIU, 178.5%, and 100%, respectively. Figure 10.19a and b shows rhombic ring resonator-based biochemical sensor design and its output spectrum at different glucose levels, respectively.

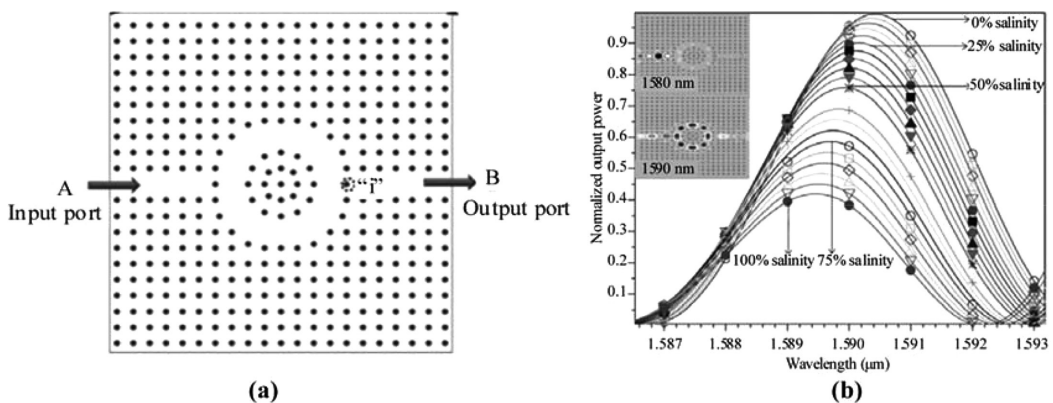
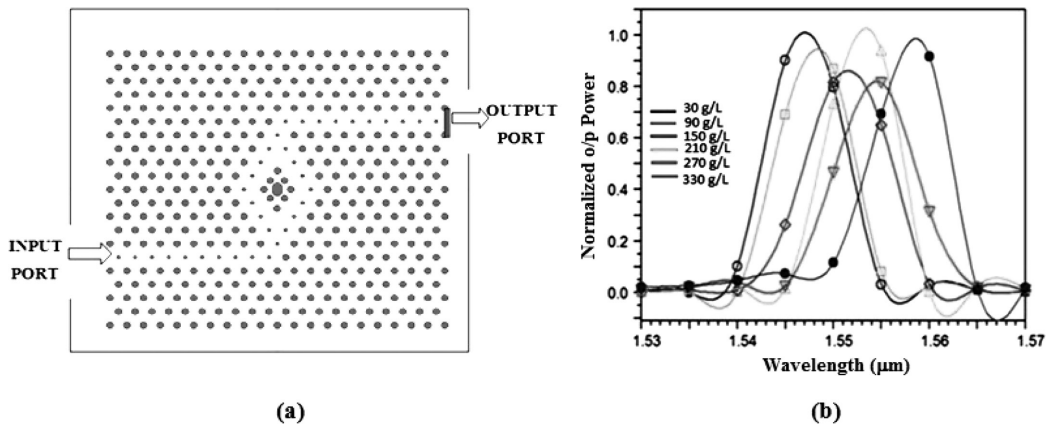


FIGURE 10.18

(a) Schematic of the circular PCRR-based sensor design and (b) normalized output spectrum at different salinity levels. (From Robinson, S. and Nakkeeran, R., *Photon. Sens.*, 2, 187–192, 2012.)

**FIGURE 10.19**

(a) Schematic of rhombic ring resonator-based biochemical sensor design and (b) output spectrum at different glucose levels. (Suganya and Robinson 2017a.)

10.13.3 PCW-Based Sulfuric Acid and Hydrogen Peroxide Sensor

Painam et al. (2016) designed label-free biochemical sensor based on PCW for the detection of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) solution concentrations. These two chemicals play a major role in chemical industry and biomedical applications. The proposed sensor structure is based on silicon on insulator (SOI) due to its mechanical and chemical stability. The PCW is created by introducing a line defect, and a single hole is placed in the middle of the PCW structure, which is filled with different concentrations of sensing sample and its concentration is detected by observing the resonance wavelength shift of the PCW.

The simulation and analysis are done by FDTD method. The result indicates that for H_2SO_4 , average device sensitivity is calculated as 35 nm/RIU. Similarly, for H_2O_2 , average device sensitivity of 9.4 nm/RIU is obtained. The coefficient of determination obtained as 95.21% and 99.59% for H_2SO_4 and H_2O_2 is very high. Moreover, optimization techniques are adopted for the sensor; both the components reach their optimum values at cavity radius 0.2 μm for H_2SO_4 and 0.23 μm for H_2O_2 with average sensitivities of 35 and 64.98 nm/RIU and standard deviation of 6.2 and 10.87, respectively. Resolution and limit of detection are calculated as 1.2 nm and 4×10^{-2} RIU for H_2SO_4 solution and 0.2 nm and 2×10^{-2} RIU for H_2O_2 solution, respectively. Figure 10.20a–c shows PCW-based biochemical sensor design, output spectrum at different concentrations for H_2SO_4 solution, and output spectrum at different concentrations for H_2O_2 solution, respectively.

10.13.4 2D PC-Based Sugar, Sodium Chloride, and Alcohol Sensor

Palai and Tripathy (2012) reported a method to measure the concentration of sugar, sodium chloride, and alcohol solution using 2D PC structure. The sensing platform consists of the

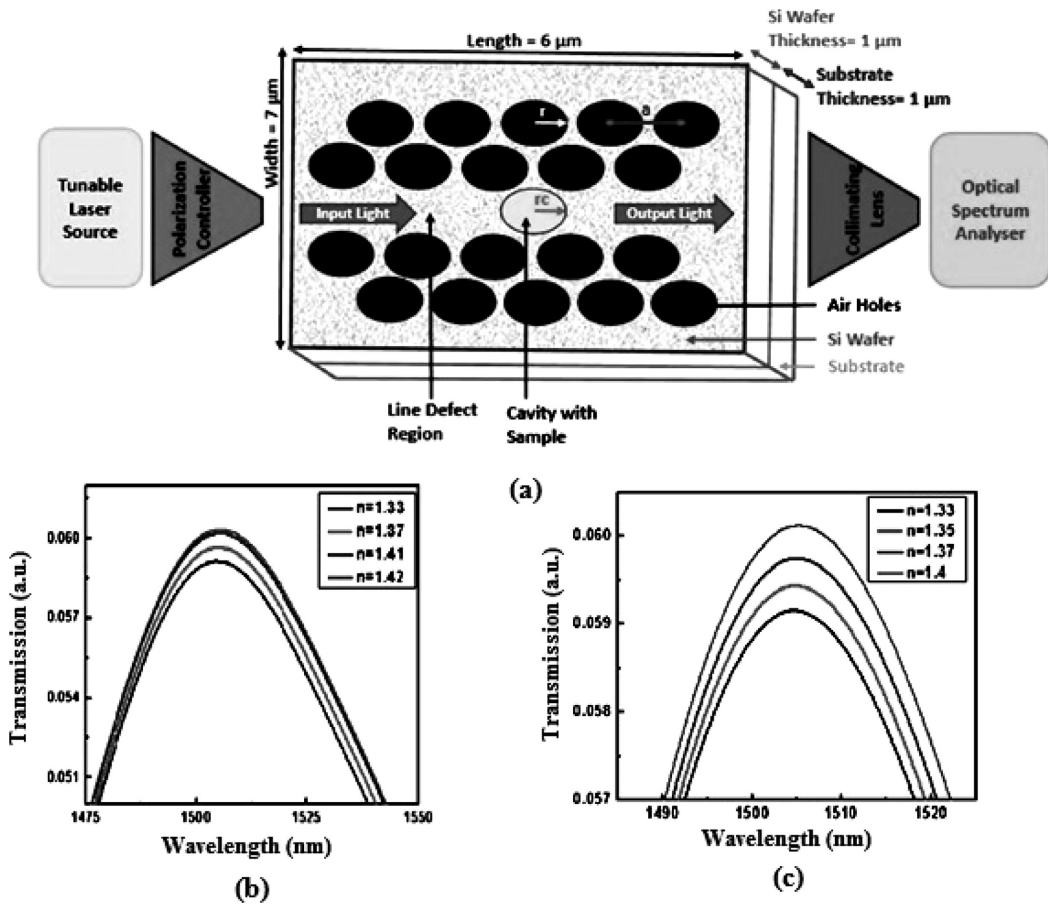
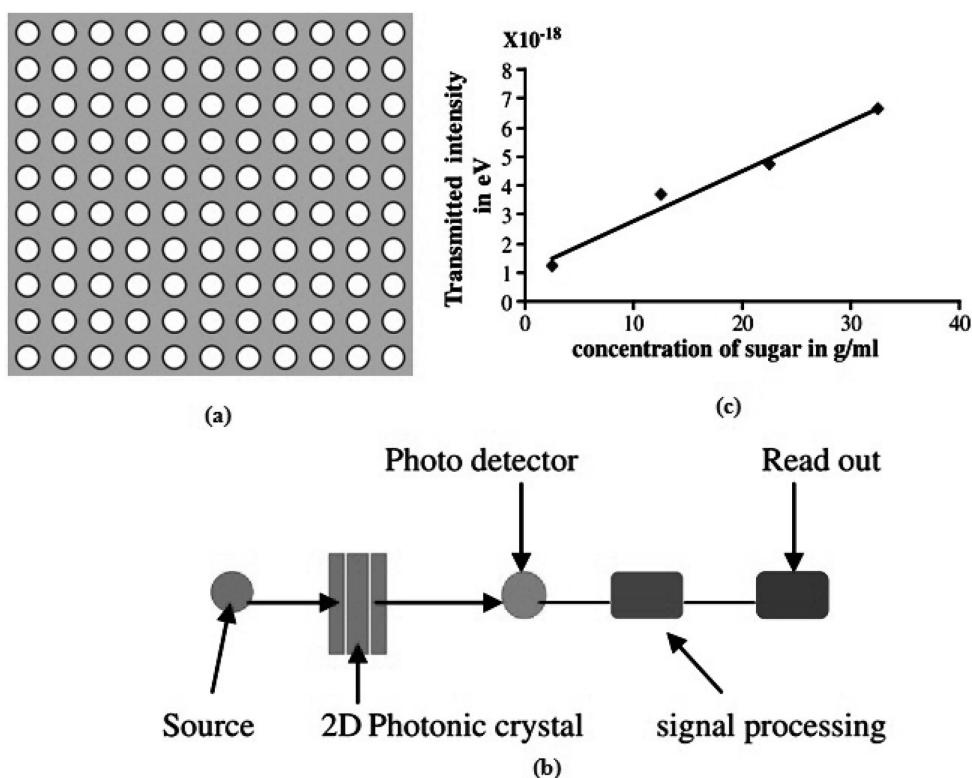


FIGURE 10.20

(a) Layout of PCW-based biochemical sensor design, (b) output spectrum at different concentrations for H_2SO_4 solution, and (c) output spectrum at different concentrations for H_2O_2 solution. (From Painam, B. et al., *Plasmonics*, 12, 899–904, 2017.)

perfect PC structure with air holes of radius $0.4 \mu\text{m}$ and a lattice constant is $1 \mu\text{m}$. The sugar, sodium chloride, and alcohol concentration are measured by the perfect PC structure, that is, it is filled within air hole as shown in Figure 10.21a, and its corresponding output is observed via PBG. The different dielectric permittivity value is considered for chemical concentration measurement. Simulation results show that the concentration of sugar increases from 7.5 to 40 g/mL, and PBG decreases from 17.791×10^{-18} to 11.171×10^{-18} eV. Similarly calculated PBG for different concentrations of sodium chloride and alcohol. These three solutions are of highly importance in medical applications. For example, sugar solution is used for hyperglycemia patients, salt solutions are used as saline for dehydrated patients, and alcohol solution is for anesthesia and antiseptic purposes. Further, sugar concentration only measured experimentally is shown in Figure 10.21b, and its value directly measured by transmission intensity level is shown in Figure 10.21c.

**FIGURE 10.21**

(a) Schematic of PC-based biochemical sensor, (b) schematic for measurement of sugar concentration experimentally, and (c) transmittance versus concentration of sugar solution. (From Palai, G. and Tripathy, S.K., *Opt. Commun.*, 285, 2765–2768, 2012.)

10.14 “PC”-Based Biosensor

10.14.1 Nanocavity-Coupled PCW-Based Cancer Cell Sensor

Saronika et al. (2016) proposed a nanocavity-coupled inline quasi PCW structure designed to detect the five different cancer cells. The sensor is designed in a triangular lattice with silicon rods arranged in air background. The line defect introduces to make inline quasi waveguide structure in input and output sides, and nanocavity is formed by a single point defect with two coupling rods and is located input and output inline quasi waveguides. First, no center rod is used to identify the resonant wavelength of biosensor at 1661 nm. Second, the center rod is placed at the middle of the structure and filled with blood sample of a normal person. The light and blood sample strongly interact with each other inside the nanocavity and its output is observed at the output spectrum. Furthermore, blood sample of different cancer cells is filled within nanocavity, and its resonant peak shifts toward the higher wavelength compared with the blood sample of a normal person. The sensor structure is further optimized to clearly identify the normal person and cancer cell with high sensitivity and high quality factor, and the optimized sensor output is obtained by Jindal et al. (2016).

10.14.2 PC Grating-Based Lymphocyte Cell Component Sensor

Sharma and Sharan (2014) demonstrated a 2D grating-based PC-based biosensor for complete analysis of normal healthy lymphocyte cell and its components for early-stage detection of cancer. The sensor design consists of square lattice platform and rods in air configuration with line defects are used in Sharma and Sharan (2014). The air is replaced by the blood sample when the sensor device is absorbed with lymphocyte cells. The light interacted with the lymphocyte cell and its components are detected using transmission and reflection spectrum with different resonant peaks, respectively. FDTD has been used for the cell analysis. If the lymphocyte cell and its refractive index are increased from normal value, then that kind of cell is treated as a cancer cell because the refractive index of normal cell is very low compared with the cancer cell.

10.14.3 PC-Based Glucose Concentration in Urine and Blood Sensor

Sharma and Sharan (2015) demonstrated and designed a 2D PC-based biosensor with a line defect used to detect the glucose concentration in urine and blood. The sensor simulation and analysis have been done using FDTD. The PC-based biosensor is used to detect the glucose concentration in normal urine (0–15 mg/dL) and urine with 0.625, 1.25, 2.5, 5, and 10 gm/dL of glucose concentration in the wavelength range of 1530–1565 nm. The biosensor design is based on a triangular lattice with rods arranged in air platform with line defect introduced to make waveguide structure. The air medium is replaced by urine sample with different concentrations of glucose when sensor dipped into urine. The light signal velocity is reduced within a waveguide structure due to filled urine sample and as a result light strongly interacts with urine sample and its normalized spectrum is used to detect different intensity levels for different glucose concentrations in urine. Similarly, different blood glucose concentrations (165–342 mg/dL) are detected and their outputs are observed by normalized spectrum.

10.14.4 PCRR-Based Glucose Concentration in Urine and Blood, Albumin, Urea, and Bilirubin Concentration in Urine Sensor

Robinson and Dhanalaskhmi (2016) designed a 2D PCRR-based biosensor to detect the glucose concentration in urine and blood and albumin, urea, and bilirubin concentration in urine over a wide DR. The PCRR structure is designed in the square lattice with silicon rods arranged in air host. Sensor is composed of two inverted L waveguides and a ring resonator as shown in [Figure 10.25a](#). The PWE and FDTD methods are used for simulation and analysis, respectively. The sensor working principle is based on the ERI, which is used to accurately detect different urine samples. The air background is replaced by different urine samples with different concentrations when sensor is dipped into urine. The light is strongly interacting with different urine samples at ring resonator, and as a result, different glucose concentrations in urine and blood and urea and bilirubin concentration in urine are accurately measured by observing the different intensity levels in resonant wavelength as shown in [Figure 10.22b–d](#).

10.14.5 PCW-Based Disease Detection Sensors

Chopra et al. (2016) proposed a 2D PCRR-based biosensor that is used to detect two different diseases such as diabetes and cancer. Also, different blood components are detected with moderate shift. The biosensor is designed in a hexagonal array of silicon rods in air

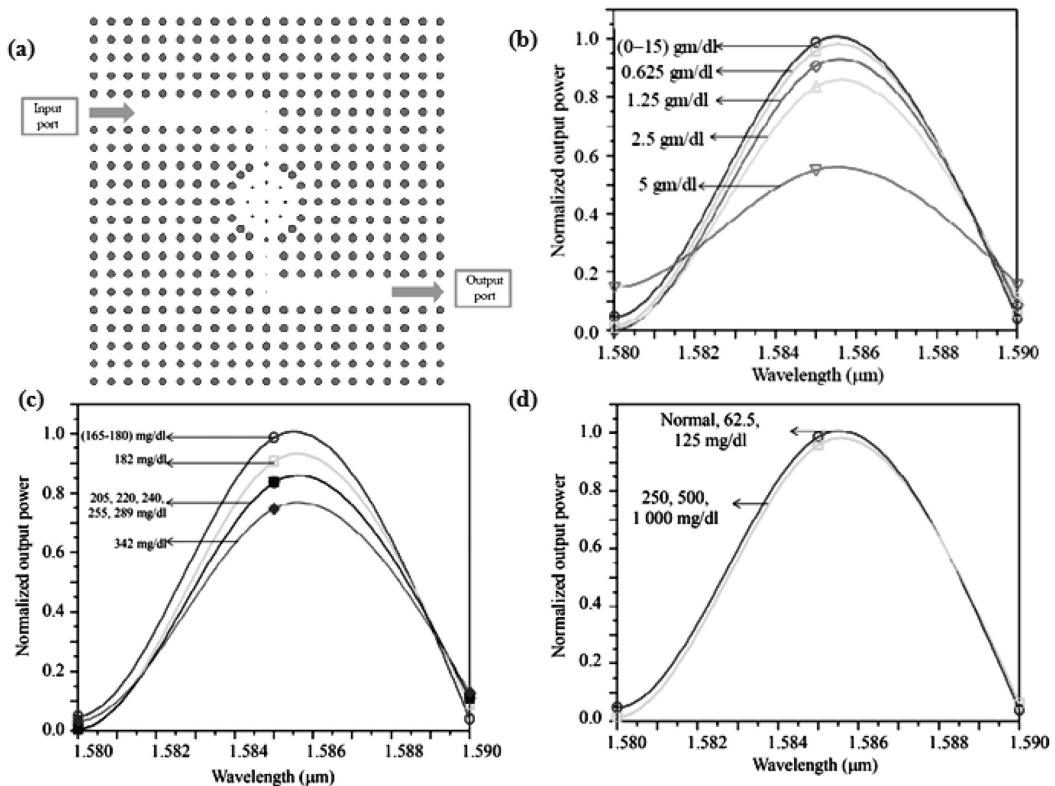


FIGURE 10.22

(a) Schematic of PCRR-based sensor, (b) transmission spectrum of different glucose concentrations in urine, (c) different glucose concentrations in blood, and (d) different concentrations of albumin. (From Robinson, S. and Dhanalaskhmi, N., *Photon. Sens.*, 7, 11–19, 2016.)

host with diamond ring resonator and two waveguides: a bus waveguide and a drop waveguide. In the diamond ring resonator, sensing mechanism is applied on the ring-shaped middle cylinder with outer radius (R) equal to 200 nm and inner radius (r) equal to 180 nm. Sensing mechanism consists of filling the inner hole of the ring-shaped middle cylinder with different analytes and strongly interaction occurs between blood and light. The detecting mechanism is based on the change in refractive index of the different analytes, leading to a shift in the peak resonant wavelength (Chopra et al. 2016), which can be used to detect different blood components, tear glucose cell, and cancer cell with a high sensitivity of 6.175 and a quality factor of 1082.2063. Chopra et al. (2016) show the transmission spectra for different blood components, cancer cells, and diabetic cells.

10.14.6 PCW-Based Detection of *Escherichia coli* Sensor

Painam et al. (2016) presented experimental and simulation analysis of PCW-based biosensor for detection of the *E. coli* cell. In this method, *E. coli* culture is used to measure length, diameter, and refractive index and to verify the suitability of PCW as a biosensor. The biosensor operating wavelength range is varying from 1132 to 1825 nm and from 0.447 to 0.66 μm for pathogen's length and diameter, respectively. Painam et al. (2016) show the

scanning electron microscope used to measure the sample distribution over length and diameter. Further, experimental values are used for simulation analysis of designed PCW biosensor. Painam et al. (2016) depicted the schematic of the PCW-based sensor. *E. coli* cell is placed in the middle of the PCW biosensor having three different types of waveguides, that is, gallium arsenide/silicon dioxide (GaAs/SiO₂), silicon/silicon dioxide (Si/SiO₂), and silicon nitride/silicon dioxide (Si₃N₄/SiO₂). Si/SiO₂ PCW obtained the highest sensitivity of 10.10438 nm/RIU, and GaAs/SiO₂ PCW shows the medium sensitivity of 2.02 nm/RIU. Si₃N₄/SiO₂ obtained the highest average sensitivity of 4.725 nm/RIU. Painam et al. (2016) show the variation in sensitivity due to change in RI. From the analysis, it is noted that GaAs/SiO₂ is the preferred PCW biosensor for the identification of *E. coli*.

10.14.7 Honeycomb Structure-Based Hemoglobin Sensor

Swain and Palai (2016) presented experimental and simulation analysis of hemoglobin concentration in human blood using 2D honeycomb PC structure. The sensor principle is based on the linear variation of both PBG and absorbances with respect to different concentrations of hemoglobin in human blood. Figure 10.23a shows honeycomb PC structure having gallium arsenide as a background material containing air holes, where blood

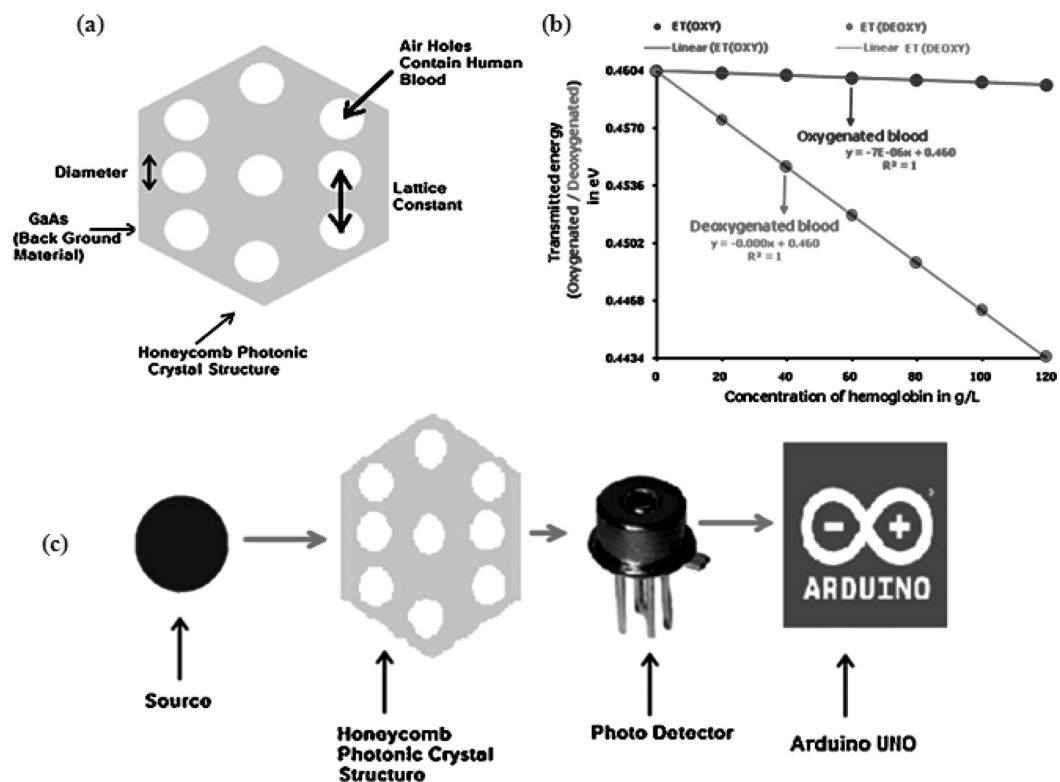


FIGURE 10.23

(a) 2D honeycomb photonic crystal structure, (b) variations of transmitting energy with hemoglobin concentration for oxygenated and deoxygenated blood, and (c) experimental setup to measure the concentration of hemoglobin. (From Swain, K.P. and Palai, G. *Optik*, 127, 3333–3336, 2016.)

with different percentage (g/L) of hemoglobin is infiltrated. The proposed structure is composed of 9 numbers of air holes such that the diameter of air holes is 420 nm and the lattice constant of the structure is 1 μm . The principle of measurement is based on the linear variation of reflected energy and absorbance with respect to the concentration of hemoglobin in human blood. As the principle is based on the linear variation of both reflected and absorbance, intensity transmitted through a honeycomb structure also varies linearly with respect to hemoglobin concentration in the blood as shown in Figure 10.23b. Furthermore, different hemoglobin concentrations in blood are detected experimentally as shown in Figure 10.23c.

10.14.8 Nanocavity-Based Glycated Hemoglobin Sensor

Olyae et al. (2016) presented that a nanocavity-coupled linear quasi PCW structure is designed to detect the glycated hemoglobin in human blood. The sensor is designed in a triangular lattice with hexagonal lattice of air holes in the slab of silicon. The line defect introduces to make linear waveguide within the structure, and nanocavity is formed by single point defect with hole radius increased from 150 to 220 nm, which is shown in Figure 10.24a. Simulation and analysis of the sensor are carried out by FDTD method. The structure is simulated for different radii of cavity, and this effect is analyzed by

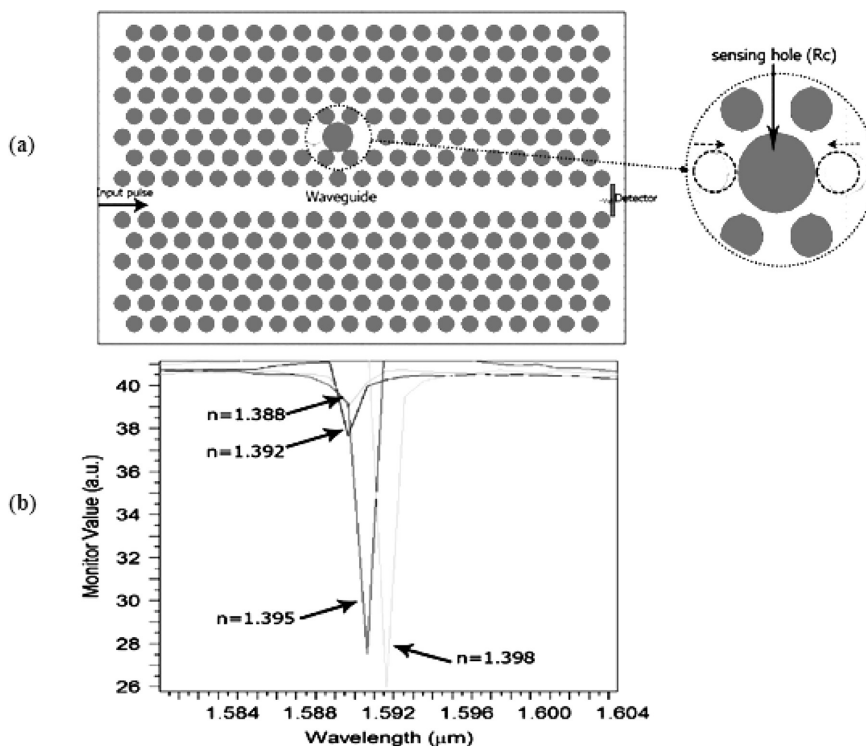


FIGURE 10.24

(a) The PC biosensor structure and (b) variations of transmitting energy with hemoglobin concentration for oxygenated and deoxygenated blood. (From Olyae, S. et al., *J. Modern Opt.*, 63, 1274–1279, 2016.)

sensing parameters on the sensitivity, quality factor, and light transmission intensity. The simulation result shows that the quality factor is 3185.2, and the sensitivity is calculated to be 133 nm/RIU. Furthermore, optimization is carried out than increasing sensitivity due to two holes adjacent to the sensing hole is shifted toward the sensing hole. Nanocavity resonator is sensitive to the refractive index variations of the sensing hole due to the strong matter–light interaction, as a result of which sensitivity is increased to 272.43 nm/RIU. The different glycated hemoglobin level is filled within a sensing hole, and its interaction with light due to resonant peak is shifted toward higher wavelength as shown in Figure 10.24b.

10.14.9 PCRR-Based Protein Concentration Sensor

Shanthi and Robinson (2016) proposed that circular PCRR-based sensor is designed to sense the protein concentration over the range from 0% to 100%. The sensing characteristics such as Q factor, resonant wavelength, pass-band width, and output efficiency are investigated. The PCRR coupled to inline quasi waveguide is the proposed design of sensor. The waveguide is configured by removing some silicon rods in input and output sides, and the circular PCRR is formed by changing the position (25%) of the inner rods shown in Figure 25a. The refractive index of the protein concentration increases linearly while increasing the level (percentage) of protein concentration. In the PC structure, an increase in the refractive index increases the resonant wavelength of the sensor shifting to the higher wavelength and vice versa. It is noticed that the refractive index around 0.0110 is increased while increasing the protein concentration by 5 percentage (%). By combining the aforementioned principle, the sensing characteristics are analyzed. If the protein is entered into the structure, the refractive index of the sensor varies according to the protein concentration, and the resonant wavelength of the sensor shifts to the higher wavelength region shown in Figure 25b.

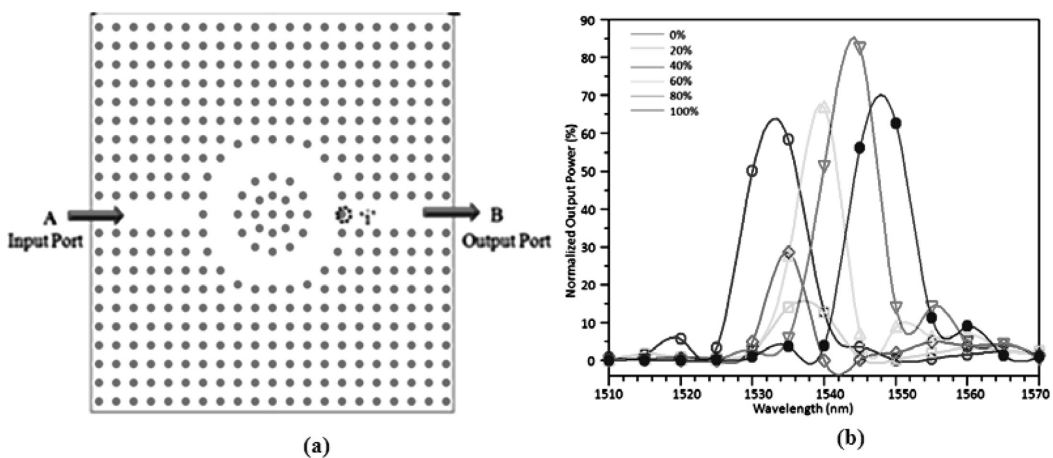


FIGURE 10.25

(a) Schematic of the circular PCRR-based biosensor and (b) normalized output spectrum at different protein concentrations. (From Shanthi, K.V. and Robinson, S., *Int. J. Opt. Photon.*, 10, 123–130, 2016.)

10.14.10 PC Nanoring Resonator-Based DNA Sensor

Hsiao and Lee (2010) theoretically investigated the sensing action based on PC nanoring resonators. The nanoring resonator is formed by removing holes in a hexagonal shape from a 2D silicon PC slab having hexagonal array of air holes in silicon. The DNA biomolecules filled in a functionalized hole that allows the resonance peak wavelength shift obtained at the output terminal. The proposed structure is a combination of both PCRR and waveguides. On optimizing its structure simulation, results show that the quality factor can be improved by increasing coupling distance but drop in efficiency. The quality factors of 2400 and 3200 are reported in the presented nanoring resonator structure with two-hole and three-hole coupling distances, respectively. The ultrasmall biomolecule detection limit for presented PCRR in a sensing hole of coupling distance two-hole and three-hole is reported as 0.23 and 0.2 fg, respectively. The nanoring resonator with coupling distance two-hole and three-hole structures and their output spectrum is measured by Hsiao and Lee (2010).

10.15 Conclusion

In this chapter, the recent advances and progress in PC-based sensors, operating principles, sensing mechanisms, functional parameters, detecting analytes, sensing platforms, and its applications are discussed. The operating principle of PC-based photonic sensor is generally based on ERI, and detecting mechanisms are mainly based on the resonant wavelength shifting because it detects minute variation of sensing sample with higher sensitivity. Furthermore, we briefly discussed about the detecting and functional parameters of different PC-based sensing platforms such as PCW, cavity-coupled PCW, and ring resonator. Among them, PC-based nanocavity is highly attractive for photonic society and edge for nanosensing applications due to which it provides tremendous Q factor, sensitivity, detection limit, and FOM. Finally, different PC-based biochemical and biosensor sensing platforms and their simulation results are elaborately reviewed. The PC-based sensor is ultracompact size, hence, highly attractive and incredible candidates in nanotechnology-based sensing devices, nano-opto-electro-mechanical systems (NOEMS), nanophotonic integrated circuits, smart industry applications, and highly advanced biomedical equipments.

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11

2D Photonic Crystal-Based Demultiplexer: A Review

Venkatachalam Kannaiyan, Robinson Savarimuthu, and Sriram Kumar Dhamodharan

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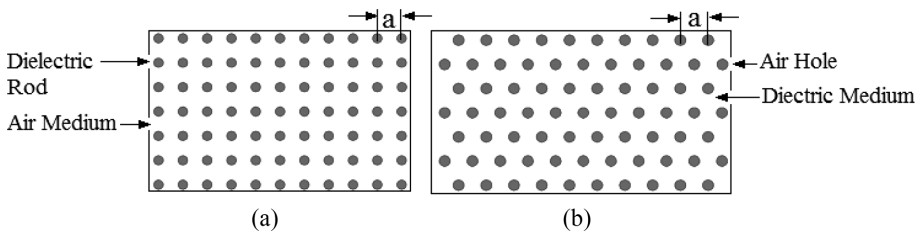
11.1 Introduction

Photonic crystals (PCs) are one of the most promising building blocks for designing compact and high-speed optical devices. They have the excellent ability to confine and control the light waves inside the compact waveguides. PC technology plays an eminent role in photonic network communication. PCs (Joannopoulos et al. 1995) are composed of periodic dielectric or metallic-dielectric nanostructure that affects the propagation of electromagnetic waves in the similar nature forbidden electronic band as the periodic potential in a semiconductor crystal affects the motion of electrons. PCs act as regularly repeating regions of alternating low and high dielectric constants. Photons propagate through the periodic structure, which depends on the wavelength. The wavelength is allowed or not allowed inside the structure is called as modes, that is, the bands or photonic bandgaps (PBGs) (Yablonovitch and Gmitter 1991). This concept causes to enhance the distinct optical phenomena such as inhibition of spontaneous emission (Bykov 1972; Yablonovitch 1987), high-reflecting omnidirectional mirrors (Bryuant 2003), and low-loss wave guiding, among others.

PCs are categorized onto one dimensional (1D), two dimensional (2D), and three dimensional (3D). The 1D PCs are structured as periodic multilayered dielectric mirrors and to use filters (Hassan et al. 2015). The 2D PCs are fabricated in the form of slab (Johnson et al. 2000), which confine the light through the total internal reflection and are used to design photonic crystal fiber (PCF) (Ward 2008) and simple optical devices such as filters (Robinson and Nakkeeran 2013a, 2013b, 2013c), logic gates (Alipour-Banaei et al. 2014; Liu et al. 2013; Singh and Rawal 2015), sensors (White and Fan 2008; Liu and Salemink 2012), encoders (Alipour-Banaei et al. 2016; Moniem 2016), decoders (Moniem 2015), switches (Cuesta-Soto et al. 2004; Wang et al. 2010), coupler circulators (Moghaddam et al. 2010; Wang and Fan 2005), splitters (Ghaffari et al. 2008; Zabelin et al. 2007), light emitting diode (LED) (Choi and Park 2014), multiplexers (Zhuang et al. 2016), demultiplexers (Alipour-Banaei et al. 2013a, 2013b; Alipour-Banaei et al. 2015; Djavid et al. 2008; Ghorbanpour and Markouei 2013; Gupta and Janyani 2014; Mansouri-Birjandi and Rakhshani 2013; Mehdizadeh and Soroosh 2015; Mehdizadeh et al. 2016; Rakhshani and Mansouri-Birjandi 2012, 2013; Rostami et al. 2010, 2011; Talebzadeh et al. 2017; Venkatachalam et al. 2017; Zhang et al. 2011, 2015), and so on. The 3D PC is composed of three-dimensional periodic natures, which are involved to design optical transistors (Arkhipkin and Myslivets 2013), lasers (Chen et al. 2010), and so on.

11.1.1 Structural Classification of 2D PC

The structural classification of 2D PC is a square lattice and triangular lattice. The square lattice is composed of periodic array of dielectric rods in an air medium, and the triangular lattice is composed of air pores in a dielectric slab. The square lattice has low dielectric strength compared with the triangular lattice, and in triangular lattice, the depth and shape of air pores strongly affect the radiation losses. Unique dimension of air pores in a triangular lattice is more difficult than that of dielectric pillars immersed in air medium for a square lattice. Hence, the proposed structure is designed using 2D PC square lattice structure as it provides low propagation loss than triangular lattice. Hence, the square lattice is mostly proposed to design PC-based devices. The square lattice (Figure 11.1a) is a periodic arrangement of dielectric rods in air medium, and the triangular lattice (Figure 11.1b) is a periodic arrangement of drilling air holes in a dielectric base.

**FIGURE 11.1**

2D PC lattice structure: (a) square (cubic) lattice and (b) triangular (hexagonal) lattice.

11.1.2 Numerical Methods

The numerical methods are involved to analyze the electromagnetic wave propagated in periodic PCs, such as plane wave expansion (PWE) method (Johnson and Joannopoulos 2001), finite difference time domain (FDTD) method (Taflove 1995), finite element method (FEM) (Pelosi et al. 1997), and transfer matrix method (TMM) (Pendry and Mackinnon 1992). The PWE and FDTD methods are the most effective method to provide accurate behavior of 2D PC. The PWE is used to calculate the PBG and describes the modes in periodic and nonperiodic dielectric structures. However, it could not predict the extract backward reflections, field distribution, and transmission spectra of the 2D PC structure. Hence an alternative approach of FDTD method is used to solve the Maxwell's equations to allow the transmission spectra of PC-based optical devices, which is one of the most successful computational techniques for analyzing the flow of electromagnetic signal propagation in PCs. It is simple, attractive, highly accurate, and efficient to obtain the output response. Generally, 1D FDTD methods provide fast simulation with less accuracy, and 1D PWE evaluates incomplete PBG; 3D FDTD methods require more simulation time, large memory size, and accurate behavior of PCs, and also 3D PWE provides complete PBG; even though 3D FDTD method affords accurate results, the same results can be obtained using 2D FDTD with less simulation time and less memory space, and Fabrication is easier than 3D PC, and also 2D PWE provides complete PBG. Hence, 2D PWE/FDTD method is considered for analyzing the electromagnetic modes propagated in the 2D PC structure.

11.1.3 Mathematical Analysis

Dimensioning structure and generating PBG are initial process to design the device. The PBG is identified by electromagnetic modes (transverse electric [TE] and transverse magnetic [TM]) propagating in a PC. PWE manipulates PBG (Joannopoulos et al. 1995; Yablonovitch and Gmitter 1991) effectively in the structure. The band diagram is carried out by solving the following Maxwell's Equations (11.1–11.6):

$$\nabla \times E + \frac{\partial B}{\partial t} = 0 \quad (11.1)$$

$$\nabla \cdot B = 0 \quad (11.2)$$

$$\nabla \times H - \frac{\partial D}{\partial t} = J \quad (11.3)$$

$$\nabla \bullet D = \rho \quad (11.4)$$

The magnetic field $H(r)$ equation is as follows:

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r) \quad (11.5)$$

Maxwell's electromagnetism is an eigen value problem for the harmonic modes of the magnetic field $H(r)$, the solution of electric field is given by the following:

$$\nabla \times \nabla \times E(r) = \left(\frac{\omega}{c} \right)^2 \varepsilon(r) E(r). \quad (11.6)$$

Figure 11.2 shows the part of the light will be coupled to the optical ring resonator. The FDTD method is used to analyze the propagation of an electromagnetic field inside the 2D PC structure in the form of transversely two polarized modes TE and TM. The 2D FDTD time stepping Equations from (11.7) to (11.9) (Yee 1996) are given as follows:

$$Ex \Big|_{i,j}^{n+1} = Ex \Big|_{i,j}^n + \frac{c\Delta t}{\varepsilon_0} \left[\frac{Hz \Big|_{i,j+1/2}^{n+1/2} - Hz \Big|_{i,j-1/2}^{n+1/2}}{\Delta y} \right] \quad (11.7)$$

$$Ey \Big|_{i,j}^{n+1} = Ey \Big|_{i,j}^n - \frac{c\Delta t}{\varepsilon_0} \left[\frac{Hz \Big|_{i+1/2,j}^{n+1/2} - Hz \Big|_{i-1/2,j}^{n+1/2}}{\Delta x} \right] \quad (11.8)$$

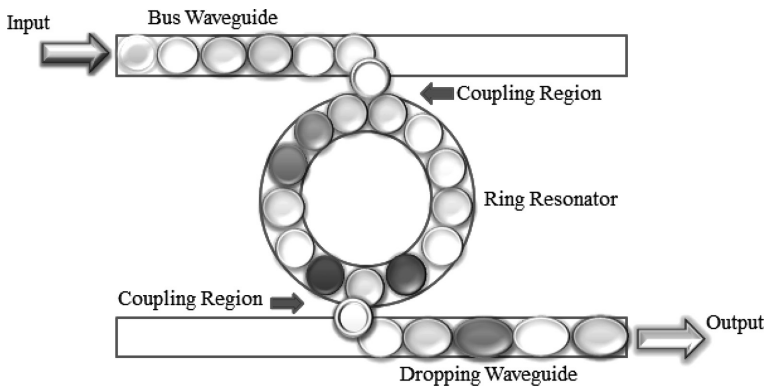


FIGURE 11.2
Signal flow diagram of ring resonator.

$$\begin{aligned}
 Hz \left| \begin{matrix} n+1/2 \\ i, j \end{matrix} \right. &= Ez \left| \begin{matrix} n-1/2 \\ i, j \end{matrix} \right. + \frac{c\Delta t}{\varepsilon_0} \left[\frac{\left[\begin{matrix} Ex \left| \begin{matrix} n \\ i, j+1/2 \end{matrix} \end{matrix} \right. - Ex \left| \begin{matrix} n \\ i, j-1/2 \end{matrix} \end{matrix} \right. \right]}{\Delta y} \right] \\
 &\quad - \left[\frac{\left[\begin{matrix} Ey \left| \begin{matrix} n \\ i+1/2, j \end{matrix} \end{matrix} \right. - Ey \left| \begin{matrix} n \\ i+1/2, j \end{matrix} \end{matrix} \right. \right]}{\Delta x} \right],
 \end{aligned} \tag{11.9}$$

where the indices “ i ” and “ j ” denote the discretized grid point in the X - Y plane and index “ n ” denotes the discrete time step.

The Gaussian signal is launched at the input port. The normalized transmission spectra are obtained by conducting fast Fourier transform (FFT) of the fields that are calculated by 2D FDTD method, which is calculated through the following formula:

$$T(f) = \frac{1/2 \int \text{real}(p(f)^{\text{monitor}}) dS}{\text{Source power}}, \tag{11.10}$$

where $T(f)$ is a normalized transmission as a function of frequency, $p(f)^{\text{monitor}}$ represents Poynting vector monitored by the power monitor at the output port of the device, and dS is the surface normal. Further normalization at the output side does not affect the result due to source power normalization. Finally, the $T(f)$ is replaced as a function of wavelength. The perfect matched layer (PML) is placed on all sides of the structure as absorbing boundary condition to avoid the reflections in the computational domain. The following numerical solution is ensured the time steps (Δt) of electromagnetic fields are propagated through n 2D PC structure accurately:

$$\Delta t \leq \frac{1}{c \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta z^2}}}. \tag{11.11}$$

The excitation of TE-polarized light is propagated in light velocity (c) along with the X - Z direction and its spatial steps are Δx and Δz .

11.1.4 Photonic Bandgap

The PBG range could be identified by assigning the structural parameter values such as lattice constant ($a \rightarrow 580$ nm), radius of rods ($r \rightarrow 1.2$ nm), and index difference ($\Delta \rightarrow 2.2$). The PBG separates air band and dielectric band. Air band or high frequency band is presented above the PBG and dielectric band or low frequency band is presented below the PBG. Typically, in [Figure 11.3](#), before introducing the defects in the structure, PBG could not allow the light signal in PC-based devices. The size of the gap is an active role to justify the working wavelength of the device.

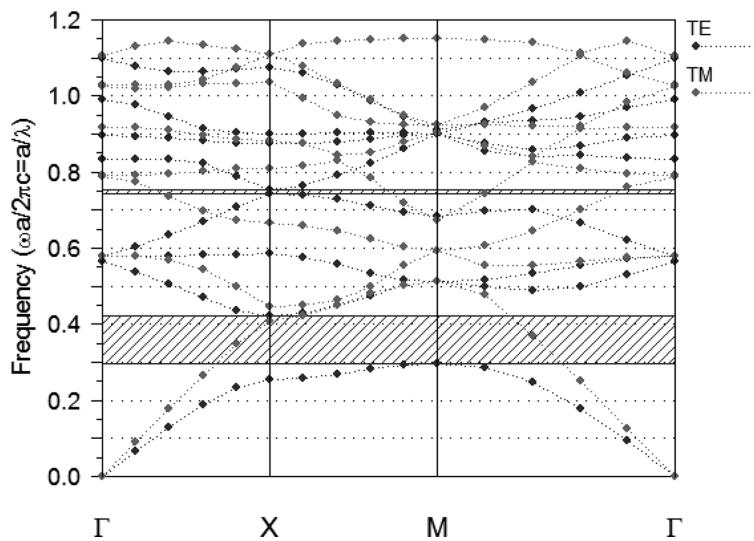


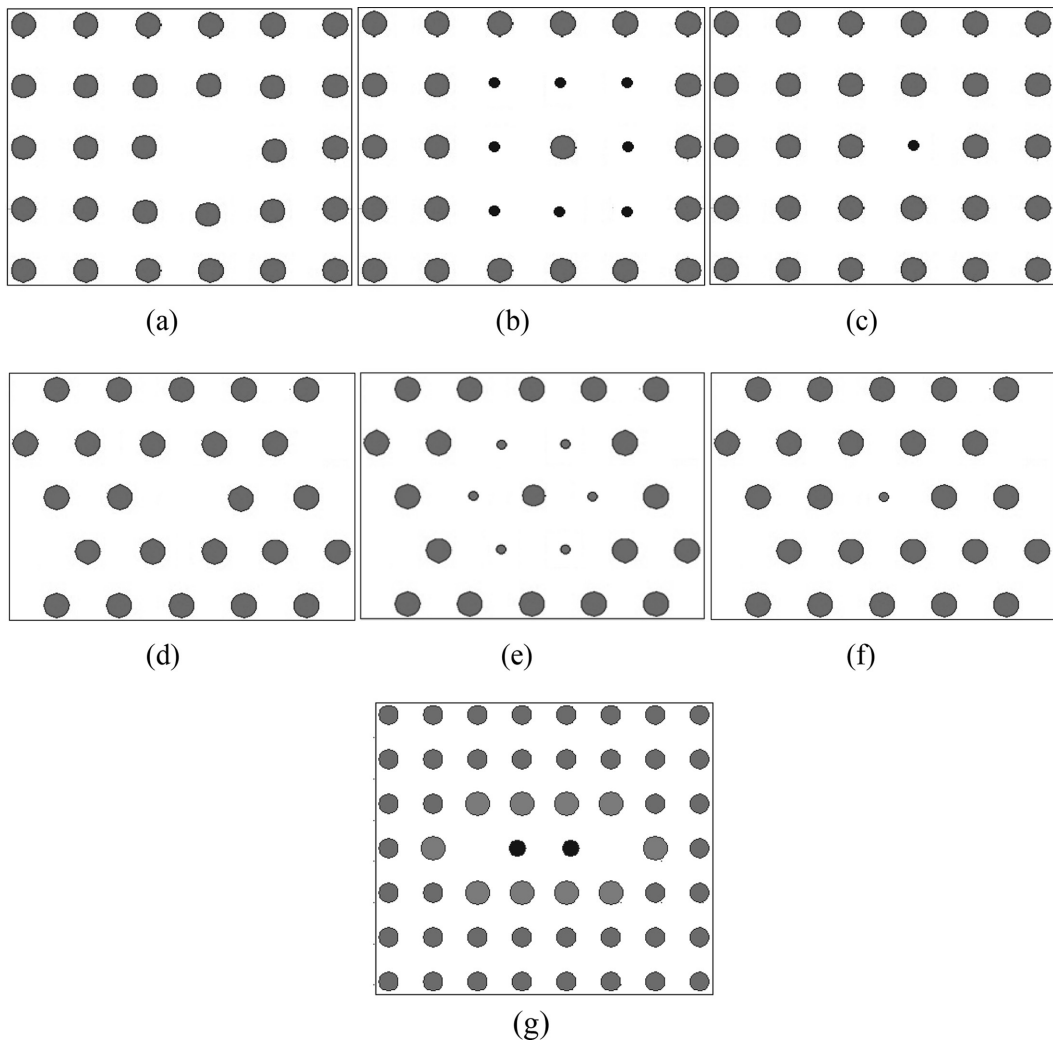
FIGURE 11.3
Bandgap structure before introducing defects.

11.1.5 Defects Introduced in 2D PC

The defects are introduced inside a structure, which breaks PBG; hence, the modes are localized that it could allow the light signal. Introduction of defects in a PC produces some shape of the component (resonant cavity, ring resonator) and ensures light propagation inside the device. The defects are classified into point, line, and surface defects. The point and line defects are mostly used to design components. The point defect is made by removing or changing a structural parameter, and the line defect is made by removing or changing a single column or row of rods. A resonant cavity is designed by the point defect, whereas linear or bus waveguide is designed by the line defect. Both the line defect and the point defect are combined to produce a ring resonator. The resonant cavity and ring resonator are acting as to filter the resonant wavelength of the device.

Resonant cavity is a tool to select a particular wavelength of the channel as shown in Figure 11.4a–g. Figure 11.4a shows square ring cavity, which is generated by removing a single rod at the center of the square lattice. The radius of rods at the center of square lattice is reduced to form a square-shaped ring cavity as shown in Figure 11.4b, and Figure 11.4 c shows the radius of a single rod, which is reduced within a square-shaped ring as point defect. In Figure 11.4d, the dimension of rods in elliptical shape can be changed to form as an elliptical ring cavity. The refractive index of rods also changed in the place of Figure 11.4b and c called as a resonant cavity. The size of the cavity depends on the selection of the channel wavelength. Hence, resonant cavity is acting as a filter to pass suitable wavelength and restrict others.

Figure 11.5a–d represents different models of ring resonator, which are designed using 2D PC. When a beam of light passes through an optical ring resonator and coupling from the waveguide, this phenomenon is happening due to the wave property of the light, principle of ray optics, and transmission effect. The following four aspects affect the optical

**FIGURE 11.4**

Different structures of resonant cavity: (a–c) square ring cavity, (d–f) hexagonal ring cavity, and (g) elliptical ring cavity.

coupling: the distance, the coupling length, the refractive indices between the waveguide, and the optical ring resonator. The effective coupling between the waveguide and the ring resonator is optimized by narrowing the distance. The coupling length also affects the coupling as well, which depends on the effective curve length of the ring resonator for the coupling phenomenon done using waveguide. If the coupling length increases, the optical coupling will decrease. The refractive index of the ring resonator material and the medium material in between the waveguide and the ring resonator also affects the optical coupling. The nature of the optical ring resonator is a filter that passes certain wavelengths of light, and its resonance wavelengths can be changed by simply increasing or decreasing the radius of each ring for effective tuning.

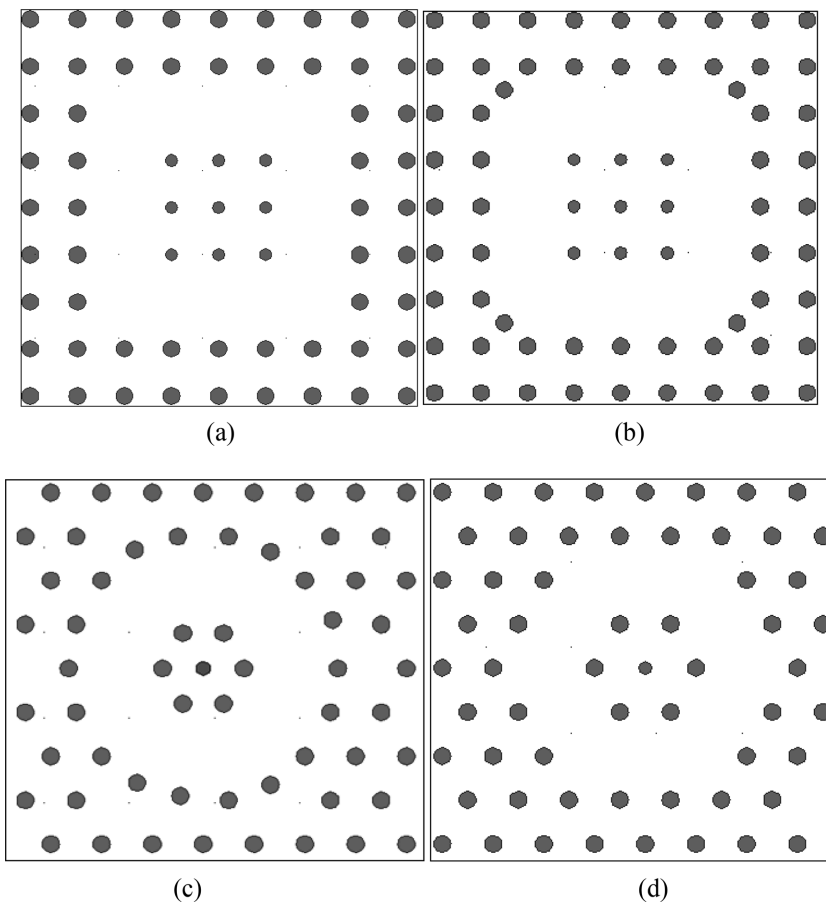


FIGURE 11.5 Different structures of ring resonator: (a) square ring resonator, (b) quasi-square ring resonator, (c) circular ring resonator, and (d) hexagonal ring resonator.

11.1.6 Wavelength Division Multiplexing Systems

Nowadays, the design of high performance with miniaturized optical devices is one of the most important technological challenges of information processing systems in optical communication. PC is one of the main players for WDM systems (Basak et al. 2013) as it offers highly wavelength sensitive, terahertz speed, and miniaturized size without degrading the performance of the device. Recently, WDM systems have received considerable interest in the research community as they support many numbers of channels with narrow channel spacing in a single fiber, which is categorized into coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (DWDM). In 2002, the ITU standardized a channel spacing grid for use with CWDM (ITU-T Recommendation G.694.2) is supporting a less number of channels over the wavelength range between 1260 and 1675 nm with 20-nm channel spacing. The main characteristic of the recent ITU CWDM standard is that the signals are not spaced appropriately for amplification by Erbium Doped Fiber Amplifier (EDFA). This therefore limits the total CWDM

optical span to somewhere near 60 km for a 2.5 Gbit/s signal, which is suitable for use in metropolitan applications. The relaxed optical frequency stabilization requirements allow the associated costs of CWDM to approach those of non-WDM optical components. CWDM is also being used in cable television networks, where different wavelengths are used for the downstream and upstream signals. In these systems, the wavelengths used are often widely separated, for example, the downstream signal might be at 1310 nm, whereas the upstream signal is at 1550 nm.

Alternatively, the DWDM system (ITU-T Recommendation G.694.1) is facilitating more number of channels, which are effective for wavelengths between approximately 1525 and 1565 nm (C band) or 1570 and 1610 nm (L band) with narrow channel spacing (1.6 nm/0.8 nm/0.4 nm). Hence, DWDM system will be used for point-to-point high capacity network; however, CWDM is used for access networks and regional networks.

The WDM systems in Figure 11.6 consist of a multiplexer, responsible for combining the signals at the transmitting end, and a demultiplexer, responsible for splitting the signals at the receiving end.

The terminal multiplexer contains a wavelength-converting transponder for each data signal, an optical multiplexer, and an optical amplifier, where necessary. Each wavelength-converting transponder receives an optical data signal from the client layer, such as synchronous optical networking or another type of data signal, and converts this signal into the electrical domain and retransmits the signal at a specific wavelength using a 1550 nm band laser. These data signals are then combined together into a multiwavelength optical signal using an optical multiplexer for transmission over a single fiber. The terminal demultiplexer consisting of an optical demultiplexer and one or more wavelength-converting transponders separates the multiple wavelength optical signal back into individual data signals and outputs them on separate fibers for client layer systems.

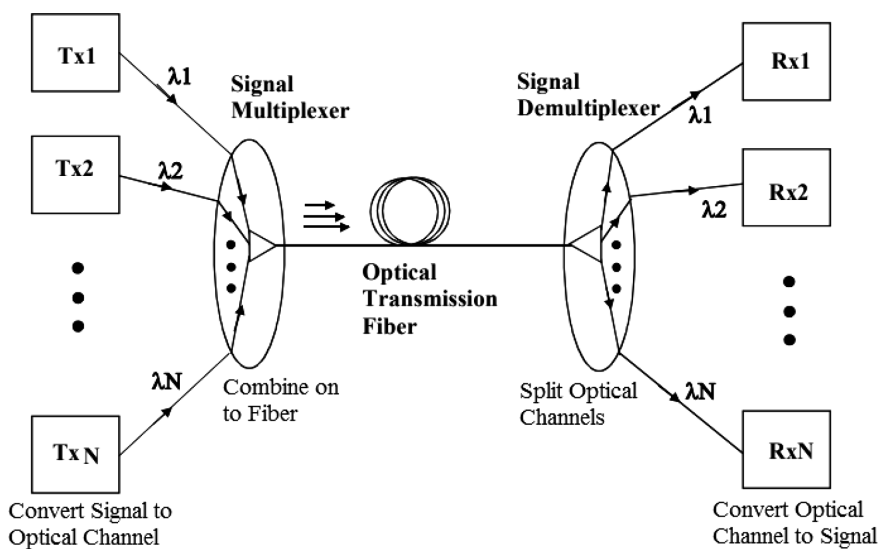


FIGURE 11.6
WDM systems.

11.1.7 WDM Demultiplexer Using PC

PCs have an excellent ability to control light wave propagation and the possibilities of implementing optical filters into WDM systems (Koshiba 2001). Using PC-based cavities and waveguides as building blocks, infinite opportunities in novel device configurations have been emerged. One of such devices is a channel drop filter that selectively drops one specific wavelength from a broadband incoming light in a waveguide, called optical add-drop multiplexers (OADMs) in WDM optical communications. A typical WDM network is enabled by important devices such as multiplexers, demultiplexers, and OADM. WDM demultiplexers are among the most important applications of PCs. Hence, one of the devices such as WDM demultiplexer is an essential part of optical communication systems. Due to the significant role of PC-based demultiplexers in the future optical communication networks, so many different mechanisms have been proposed for designing all optical wavelength demultiplexers. The demultiplexer is designed using a square lattice and a triangular lattice. One common mechanism is using the superprism effect of PCs. For instance, a superprism-based structure has been proposed by Bernier et al. (2008) by creating an efficient balance between the wavelength dispersion and the beam divergence, which has four output channels with channel spacing equal to 25 nm and crosstalk level better than -16 dB. Another common mechanism is using heterostructure devices. This kind of optical demultiplexers are obtained by cascading multiple optical filters with different structural parameters such as refractive index or lattice constant. In this kind of demultiplexers, the total structure has the same refractive index and lattice constant, and only the resonant parts of the structure are different from each other.

11.1.8 Functional Parameters

The 2D PC-based WDM demultiplexer performance is evaluated by the following functional parameters:

- Transmission efficiency (η)
- Channel spacing (λ_L)
- Spectral width ($\Delta\lambda$)
- Quality factor (Q)
- Crosstalk (X_{ij})

Transmission Efficiency

The transmission efficiency (η) is one of the important parameter in PC-based devices, which is used to calculate signal intensity level or output signal power. The transmission efficiency is calculated by the following equation:

$$p = \frac{p_O}{p_I}, \quad (11.12)$$

where P_O is the output power at the resonance peak and P_I is the input power at the same wavelength. The transmission efficiency value should be high, that is, 100%, which is obtained by reducing the coupling loss between nanocavity and waveguide. In some cases (within resonator), transmission efficiency exceeds 100%

owing to the constructive inference, in this situation, the optimum value of signal power is launched into PC waveguide to cavity.

Channel Spacing

In Figure 11.7, it is noticed that the channel spacing (λ_L) is the difference between resonant wavelengths of the simultaneous channels, which is used to measure the crosstalk between the channels. If channel spacing is high, the crosstalk between the channels is very low. Otherwise the crosstalk will be high.

Spectral Width

From Figure 11.8, it is shown that the spectral width ($\Delta\lambda$) is the full-width half-maximum (FWHM) of the channel wavelength.

Quality factor

Quality factor (Q) is the widely used for the measurement of light confinement in PC cavity. The three types of losses are of primary concern: bending loss, leakage loss,

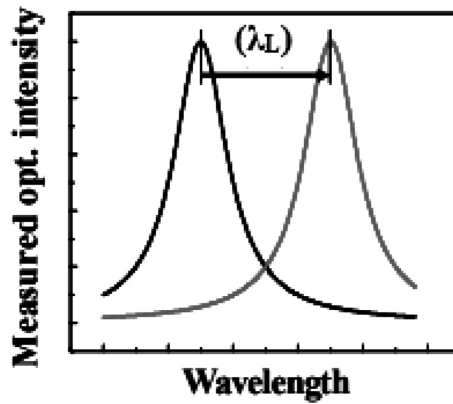


FIGURE 11.7
Schematic of channel spacing calculation.

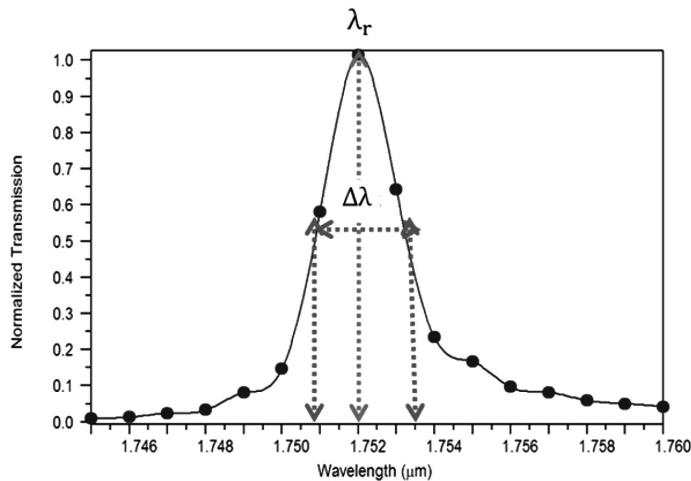


FIGURE 11.8
Schematic of quality factor calculation.

and scattering loss. Generally, bending loss and leakage loss are very low so eliminated within a structure. Scattering loss is caused by a physical surface roughness, produced at the time of fabrication. Thus, scattering loss is the primary loss, which is minimized to achieve high Q factor. Numerically, the Q is defined as the ratio of resonant wavelength to change in the wavelength at FWHM.

$$Q = \frac{\lambda_r}{\Delta\lambda}, \quad (11.13)$$

where λ_r is the resonant wavelength and $\Delta\lambda$ is the wavelength difference at FWHM.

In energy point of view, Q can also be defined as follows:

$$Q = \frac{\text{Energy stored in cavity}}{\text{Energy loss in cavity}} \quad (11.14)$$

Therefore, to achieve high Q factors, the entire cavity losses need to be minimized (Kwon et al. 2008). The Q value calculation is shown in [Figure 11.8](#).

Crosstalk

Typically, the crosstalk (X_{ij}) is calculated between the two channels, which are described in X_{ij} , where i and j represent the channel number (i.e., X_{12} represents the crosstalk value between channels 1 and 2 and vice versa), which is calculated by the natural logarithm of the ratio of the cross power point between the channels to a maximum power of the neighboring channel.

11.2 Design of Resonant Cavity-Based 2D PC WDM Demultiplexer

Typically, point defect introduced in a PC develops resonant cavity, which is a small-sized part in a device to drop the channel. The channel wavelength range depends on the dielectric strength, which is related to the shape and size of the cavity, which is used to tune the channel sharply. The following chapters are demonstrated to design different shaped resonant cavity-based demultiplexers.

11.2.1 Four-Channel Demultiplexer Based on the Modified-T PC Structure

The 2D PC triangular lattice is chosen to design the four-channel demultiplexer by Rostami et al. (2010), which is composed of three layers (SiO_2 -Si- SiO_2). The radius of air pores inside the silicon layer is $R = 115$ nm and the lattice constant is $a = 420$ nm. The structure consists of four distinct resonance cavities. The size of the defect is introduced in the resonant cavity usable to act as a filter for capturing the suitable wavelength of the channels.

In [Figure 11.9](#), the air pores in the cavities are equal to 75, 79, 83, and 87 nm radius from bottom to top. The channels are dropped at the respective dropping waveguide. The closed end of the dropping waveguide has a single defect, which is to reflect the channel properly.

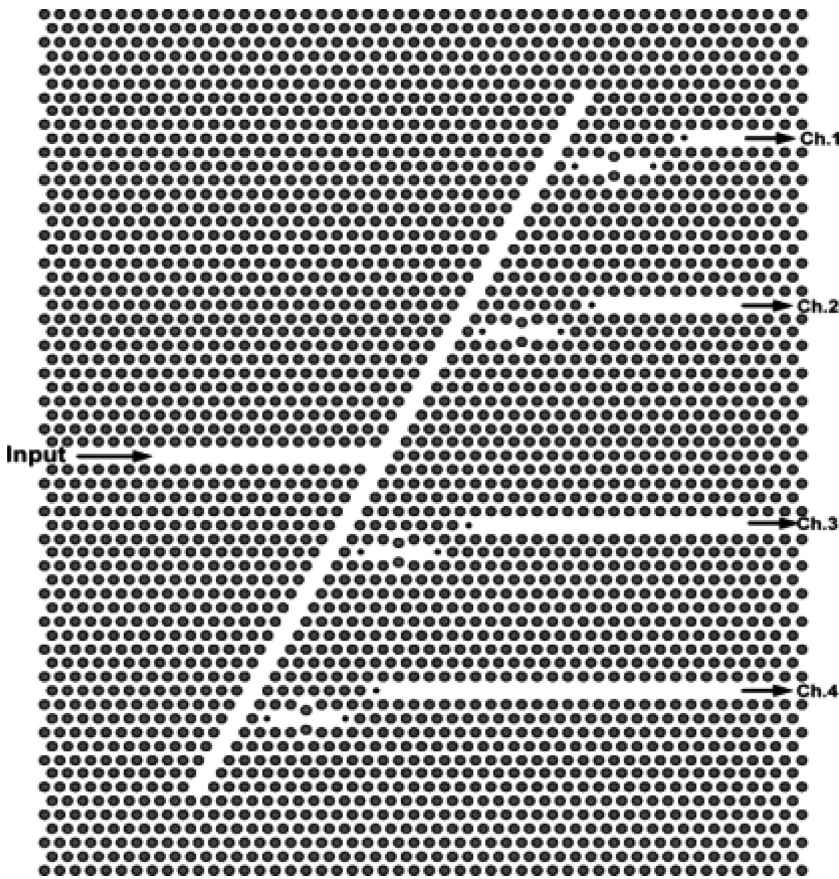


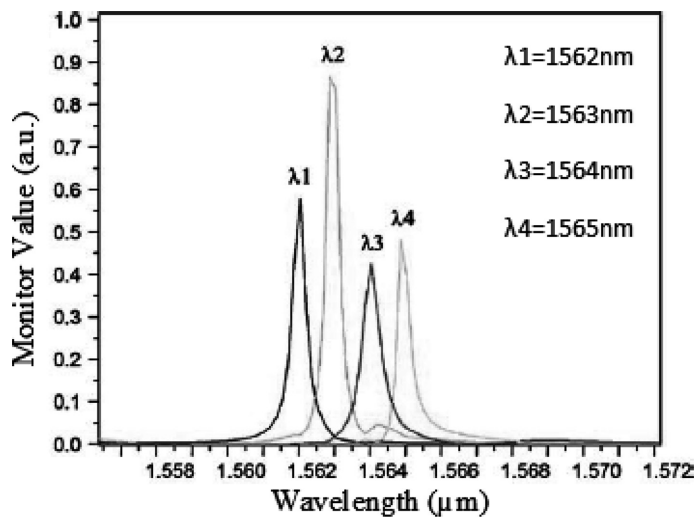
FIGURE 11.9

Complete sketch of the four-channel demultiplexer based on the modified-T PC structure. (From Rostami, A. et al., *Photon. Nanostruc. Fundamen. Appl.*, 8, 14–22, 2010.)

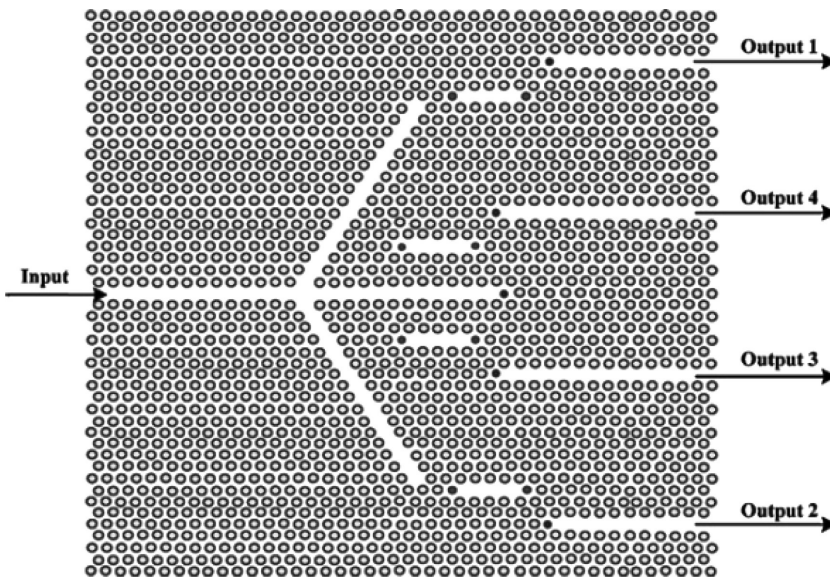
From Figure 11.10, it is noticed that four distinct channels (Ch 1 [λ_1], Ch 2 [λ_2], Ch 3 [λ_3], and Ch 4 [λ_4]) are selected from the device, and the crosstalk values are measured between the channels. This is the first device for demultiplexer to get 0.8-nm channel spacing, -18.77 dB average crosstalk, and $4170 Q$. The tuned resonant wavelengths are about 1562.6, 1563.3, 1564.1, and 1564.9 nm. The overall size is $536 \mu\text{m}^2$.

11.2.2 Four-Channel Demultiplexer Based on the Modified-Y Branch Structure

Rostami et al. (2011) determine four-channel demultiplexer, which contains Y-shaped waveguide, each arm of this waveguide has resonant cavity and dropping waveguide is designing at triangular 2D PC in Figure 11.11. The PBG is a key element to design the device, which is generated only for the TE polarization modes, that is, all of simulations are performed in TE mode for this demultiplexer structure. The PBG is in the range of $1395 \text{ nm} < \lambda < 1673 \text{ nm}$. The cross-section of the structure is $313.28 \mu\text{m}^2$. The structure is organized into three parts. First one is named as line defect that contains an input waveguide.

**FIGURE 11.10**

Linear scale spectral output for the four channels. (From Rostami, A. et al., *Photon. Nanostruc. Fundamen. Appl.*, 8, 14–22, 2010.)

**FIGURE 11.11**

Four-channel demultiplexer based on the modified-Y branch structure. (From Rostami, A. et al., *Photon. Nanostruc. Fundam. Appl.*, 122, 1481–1485, 2011.)

The second part shown in Figure 11.11 is creating a resonance cavity. The third part in the structure has an output waveguide (dropping waveguide) that contains a defect in the corner. The radius of defects in the cavity is equal to 98, 93, 88, and 83 nm.

From the simulation, Figure 11.12 is noticed that the bandwidth of each channel is nearly about 1 nm and the channel spacing is approximately 3.5 nm and the resonant wavelengths of the channels are 1548.8 nm (λ_1), 1551.9 nm (λ_2), 1555.4 nm (λ_3), and 1559.3 nm (λ_4), respectively.

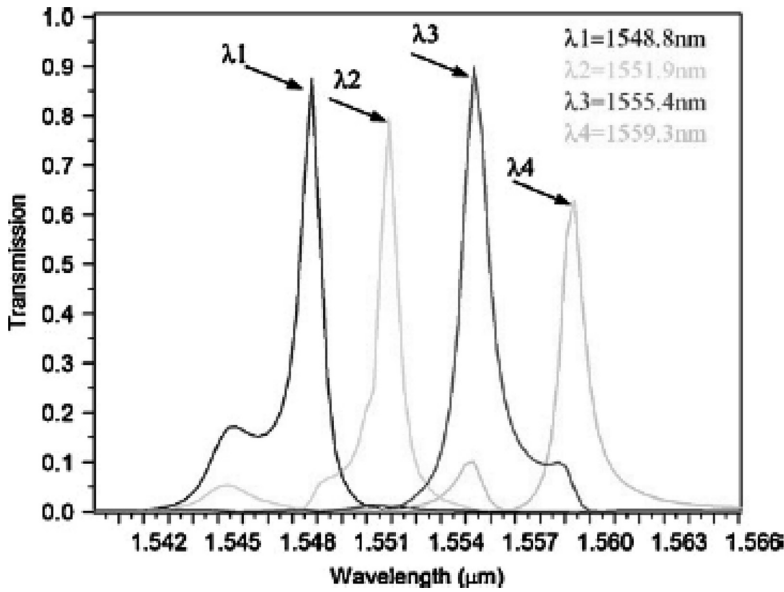


FIGURE 11.12

Output spectrum of the demultiplexer. (From Rostami, A. et al., *Photon. Nanostruc. Fundam. Appl.*, 122, 1481–1485, 2011.)

The crosstalk of the channels is measured in between -33.1855 and -10.4947 dB. The mean values of the crosstalk and Q are -22.54 dB and 1496.7 , respectively. Hence, the result is mentioned that the shift of wavelengths is tuned by removing more or less number of air pores in the cavity, and the size of the defect is introduced at the end of the cavity.

11.2.3 Square Array Cavity-Based WDM Demultiplexer

Zhang et al. (2011) reported ultracompact wavelength division demultiplexer based on the PBG. The 2D PC triangular lattice of air hole in a GaAs dielectric slab with a refractive index of 3.4, the radius of air holes $r = 0.4a$, and the lattice constant $a = 0.500 \mu\text{m}$. The PWE method is simulated to generate PBG for TE modes, which extends from 0.2501 to 0.4075 (a/λ). The device composed in the X - Z plane is 25×25 array of air holes. The reported device has two regions with the same lattice constant as shown in Figure 11.13.

The Region 1 is composed of hexagonal pattern of air holes with radius $0.372a$ and Region 2 uses a cubic pattern with a radius $0.400a$. Hence, the structures of Regions 1 and 2 have the bandgap of $0.2349 \leq a/\lambda \leq 0.363$ and $0.3736 \leq a/\lambda \leq 0.4195$, respectively. The author clearly noticed that the frequency $a/\lambda_1 = 0.3817$ falls inside of the PBG of Region 2 and falls outside of Region 1. Similarly, the frequency $a/\lambda_2 = 0.3356$ falls outside of Region 2 and falls inside of Region 1.

According to the FDTD simulation, Figure 11.14 shows the radius of the defect region, which shows that the wavelengths of 1310 and 1490 nm will output from Port A and Port B, respectively.

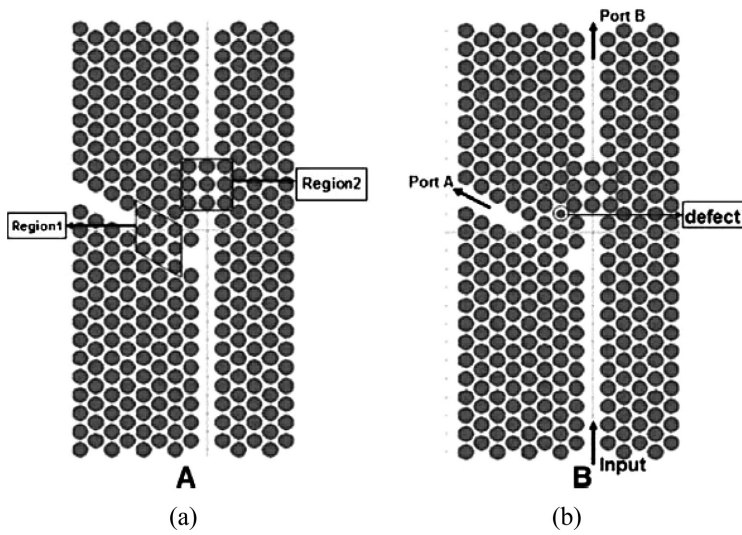


FIGURE 11.13

(a) Schematic configuration for the WDDM with a triangular lattice, which consists of two different regions and two output ports, and (b) optimization of the structure, the radii of the defect hole are selected as $R_d = 0.12a$. (From Zhang, X. et al., *Opt. Commun.*, 285, 274–276, 2011.)

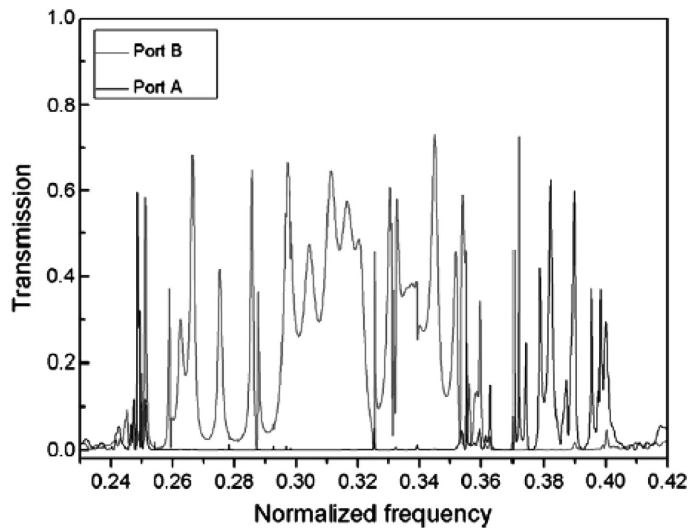


FIGURE 11.14

Output spectrum of WDDM. (From Zhang, X. et al., *Opt. Commun.*, 285, 274–276, 2011.)

11.2.4 Square Cavity-Based Eight-Channel Demultiplexer

Hamed Alipour-Banaei et al. (2013a) reported eight-channel demultiplexer using a square lattice is shown in Figure 11.15.

The structural parameters of the structure: Refractive index (n) = 4.2, radius of rod (r) = 116 nm and lattice constant (a) = 600 nm. PWE method is used on the base structure, which observes that there are three PBG regions in the band structure. The frequency

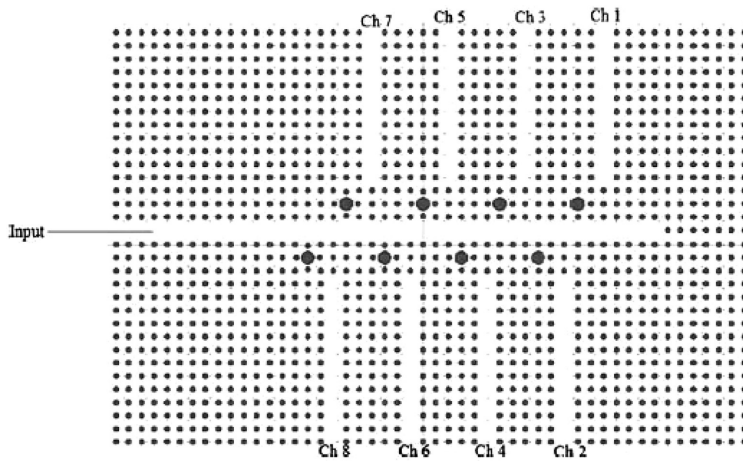


FIGURE 11.15
Schematic of the eight-channel demultiplexer. (Alipour-Banaei et al. 2013a.)

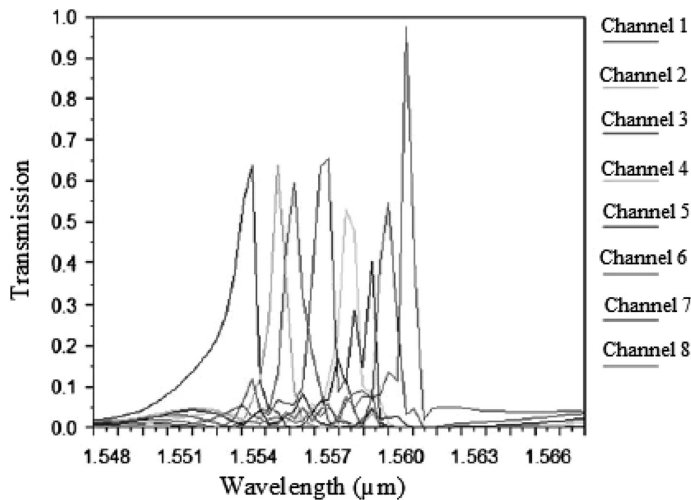


FIGURE 11.16
Output spectra of the eight-channel demultiplexer. (Alipour-Banaei et al. 2013a.)

range of PBG regions is $0.246 < a/\lambda < 0.393$ and $0.668 < a/\lambda < 0.692$, which are equal to the wavelength range of $1526 \text{ nm} < \lambda < 2439 \text{ nm}$ and $867 \text{ nm} < \lambda < 898 \text{ nm}$, respectively. The first PBG region is suitable for designing optical devices suitable for DWDM applications. The reported demultiplexer is composed of three parts: horizontal waveguide as input waveguide, eight vertical waveguides as output waveguides, and eight resonant cavities as tuning mechanism of channel wavelength of the demultiplexer. Each resonant cavity has a center rod with 301 nm, which is around by four rods with different radius for the respective channels such as 0, 10, 20, 30, 40, 45, 50, and 55 nm as shown in Figure 11.16.

This demultiplexer is simulated to obtain eight channels, which are λ_1 (Ch 1) = 1,554.3 nm, λ_2 (Ch 2) = 1,555.5 nm, λ_3 (Ch 3) = 1,556.5 nm, λ_4 (Ch 4) = 1,557.5 nm, λ_5 (Ch 5) = 1,558.3 nm,

λ_6 (Ch 6) = 1,559.4 nm, λ_7 (Ch 7) = 1,560 nm, and λ_8 (Ch 8) = 1,560.5 nm. Figure 11.16 shows the minimum transmission efficiency is 40% and the bandwidth and minimum Q is 1.1 nm and 1430, respectively.

11.2.5 X-Shaped Ring-Based Four-Channel Demultiplexer

The device composed of 44×31 dielectric rods in the row and column wise which are immersed in air in Alipour-Banaei et al. (2013b). The structural parameters are as follows: an effective refractive index (n) of dielectric rods is 4.15, the radius (r) of the rods is 121 nm, and the lattice constant (a) is 607 nm. The four-channel demultiplexer consists of one horizontal bus waveguide, four dropping output waveguides in the upper and lower parts of the structure, and four resonant X-shaped rings located between the bus waveguide and each output waveguide. The wavelength selectivity is justified by four scattering rods above and below the X-shaped rings, and the channel selection is controlled by another four defects in every X-shaped ring in Figure 11.17. The scattering rod radii are 90, 117, 90, and 90 nm, and the radius of the defect rod of four X-shaped rings is 80, 90, 110, and 120 nm.

As shown in Figure 11.18, the X-shaped rings of the demultiplexer are simulated and separated four channels with a resonant wavelength equal to $\lambda_1 = 1563.5$ nm,

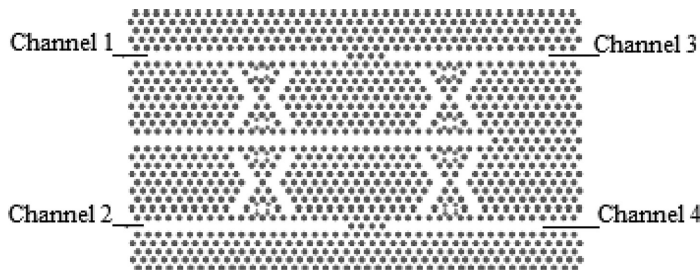


FIGURE 11.17

Schematic diagram of X-shaped rings based on the four-channel demultiplexer. (Alipour-Banaei et al. 2013b.)

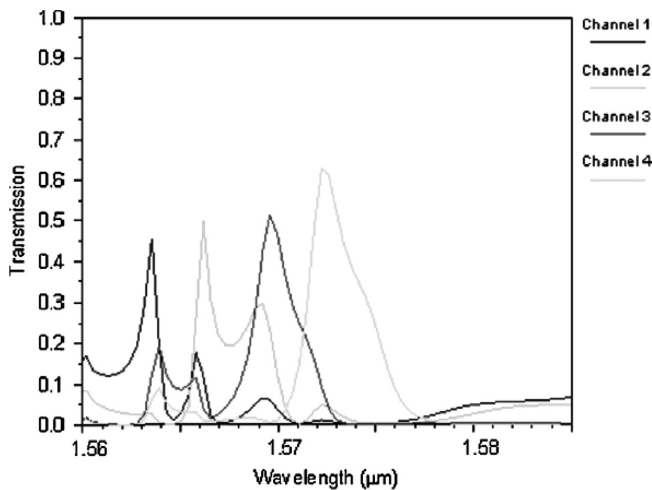


FIGURE 11.18

Linear scale output spectrum of the four-channel demultiplexer. (Alipour-Banaei et al. 2013b.)

$\lambda_2 = 1566.2$ nm, $\lambda_3 = 1569.7$ nm, and $\lambda_4 = 1572.6$ nm. The maximum and minimum transmission efficiencies of the demultiplexer are 63% and 45%, respectively.

11.2.6 Elliptical Ring Cavity-Based Four-Channel DWDM Demultiplexer

Gupta and Janyani (2014) reported a 51×51 array fundamental structure of the device, and it has a background index of 1.4 (SiO_2), a rod index of 3.47 (GaAs), an index difference of 2.07, a lattice constant or period (a) of 430 nm, a radius of nondefected rods (r) of 120 nm, and a width of 2 μm . In Figure 11.19, the demultiplexer is composed of four selective mechanisms, which are differentiated by introducing point defects and are increasing from the lower part of the structure as 119.5, 119.7, 120.0, and 120.2 nm, and the corresponding channel wavelengths filtered out through these cavity defects are 1558.9, 1559.7, 1560.6, and 1561.3 nm.

In Figure 11.20, it is noticed that the channel wavelengths are 1558.9, 1559.7, 1560.6, and 1561.3 nm, respectively. The device is capable to demultiplex input TE-polarized signal with 0.8-nm channel spacing and average bandwidth of about 0.2 nm. The average value of the Q factor of this device is about 7800.

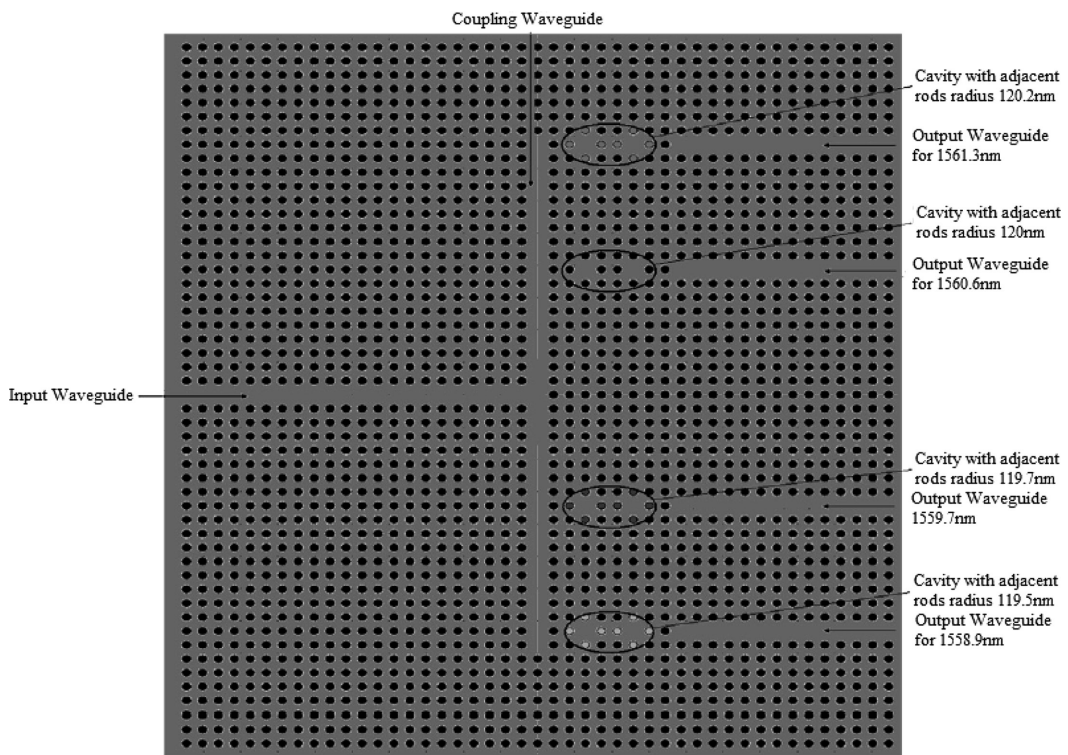


FIGURE 11.19

Elliptical ring cavity-based DWDM demultiplexer. (From Gupta, N.D. and Janyani, V., *Optik*, 125, 5833–5836, 2014.)

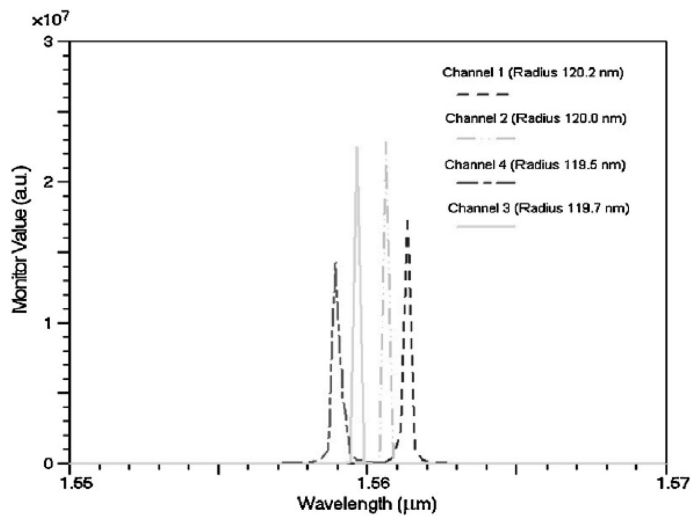


FIGURE 11.20

Output spectrum of DWDM demultiplexer. (From Gupta, N.D. and Janyani, V., *Optik*, 125, 5833–5836, 2014.)

11.2.7 Linear Array Cavity-Based Eight-Channel Demultiplexer

Mehdizadeh and Soroosh (2015) investigated 40×40 arrays of dielectric rods in a cubic lattice for eight-channel demultiplexer. The effective refractive index of dielectric material is 3.48, and the radius of rods to lattice constant ratio is 0.2. The PWE manipulated PBG range of the reported work has $1390 \text{ nm} < \lambda < 2035 \text{ nm}$. The device in Figure 11.21 is composed of the eight resonant cavities, which are 2, 7, 12, 17, 22, 27, 32, and 37 nm. The overall footprint of the proposed structure is about $495 \mu\text{m}^2$.

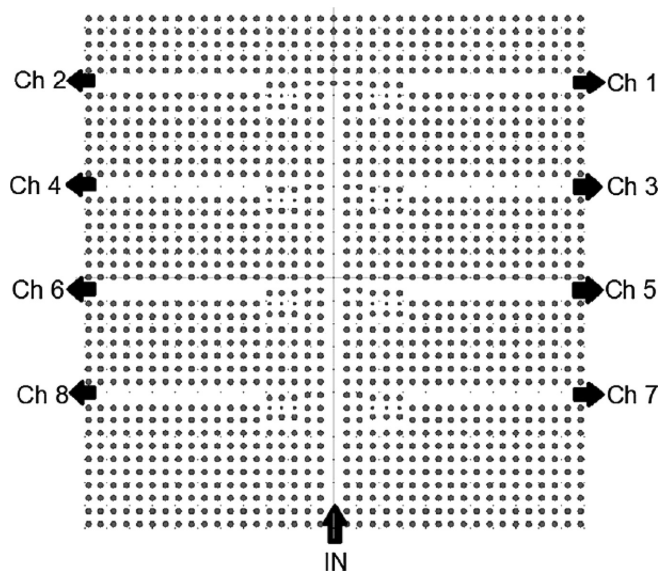
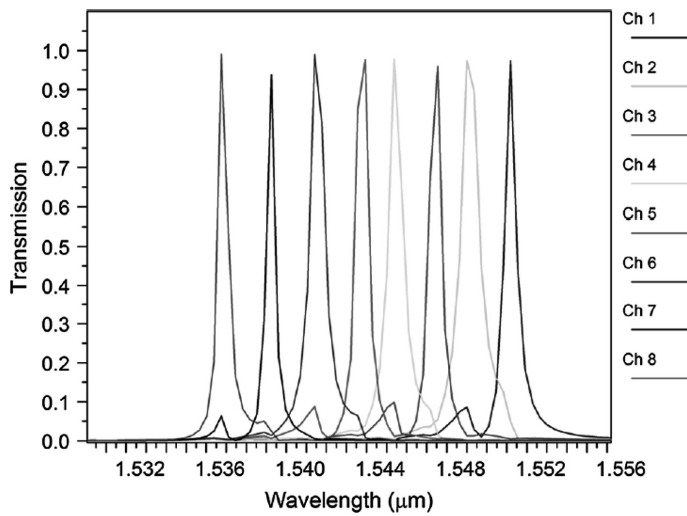


FIGURE 11.21

Linear array cavity-based eight-channel demultiplexer. (From Mehdizadeh, F. and Soroosh, M., *Photon. Netw. Commun.*, 48, 1–12, 2015.)

**FIGURE 11.22**

Linear scale output spectrum of eight-channel demultiplexer. (From Mehdizadeh, F. and Soroosh, M., *Photon. Netw. Commun.*, 48, 1–12, 2015.)

The 2D FDTD-simulated output spectrum of the demultiplexer is shown in [Figure 11.22](#). The filtered eight channels through these cavities with central wavelengths are equal to $\lambda_1 = 1551.4$ nm, $\lambda_2 = 1549.3$ nm, $\lambda_3 = 1547.6$ nm, $\lambda_4 = 1545.6$ nm, $\lambda_5 = 1543.9$ nm, $\lambda_6 = 1541.6$ nm, $\lambda_7 = 1539.4$ nm, and $\lambda_8 = 1536.9$ nm. The minimum transmission efficiency of Channel 2 (Ch 2) is 94%.

The obtained minimum and maximum bandwidths are 0.4 and 1 nm, respectively; therefore, the minimum and maximum Qs will be 1549 and 3842, respectively. The cross-talk level of the structure varies from -11.2 to -40 dB.

11.2.8 Multichannel Multiplexer/Demultiplexer

Zhuang et al. (2016) reported a resonant cavity-based DWDM multi/demultiplexer using 2D PC. A 2D PC-based multichannel multiplexer/demultiplexer with 100-GHz channel spacing is reported by Zhuang et al. (2016). The demultiplexer is made up of a triangular lattice of air holes in silicon ($\epsilon_{si} = 11.56$). The radius of air holes is $r_0 = 0.35a$, where the lattice constant $a = 451.78$ nm. The structure has three channels (Channel 1, Channel 2, and Channel 3—composed of an ordinary line-defect waveguide). On Channel 1, the radius of the resonator is $r_1 = 281.3$ nm, and the resonant frequency is 193.4 THz. The radius of the blue air holes is $r_2 = 159.5$ nm, and the distances between the resonator and the two reflectors are, respectively, $L_1 = 8a$ and $L_2 = 12a$. On Channel 2, the radius of the resonator is $r_3 = 281.2$ nm, and the resonant frequency is 193.3 THz. The radius of the blue air holes is $r_4 = 158.3$ nm, and the distances between the resonator and the two reflectors are the same as Channel 1.

In the circulator region, the central defect cavities are $r_5 = 214.9$ nm. The red air holes connecting the cavities and waveguides have a radius $r_6 = 117.4$ nm. When the distances between the resonator and the two reflectors are both $10a$, that is, $L_1 = L_2 = 10a$, the radius of the blue air holes in the phase adjustment region is used for fine tuning the light at a

frequency about 193.4 THz, which reaches the maximum transmission efficiency. If the distances between the resonator and the two reflectors are changed to $L1 = 9a$, $L2 = 11a$ or $L1 = 8a$, $L2 = 12a$, the high transmission efficiency at 193.4 THz can also be achieved. The transmission spectrum of these three cases is shown that when the distances are, respectively, $L1 = 8a$ and $L2 = 12a$, the bandwidth is the narrowest and the structure could be applied in the DWDM system with 100 GHz spacing, respectively. In the same way, the structure of the NBF is designed for other frequencies by changing the radius of the air hole in the resonant cavity.

The waveguides with Port B and Port C can filter at the wavelengths $\lambda2$ and $\lambda3$, respectively, while the waveguides with Port A and Port B are ordinary waveguides. In the multiplexer side, $\lambda1$ inputs from Port A and rotates into the waveguide with Port B after passing through the first resonator. Because of the fact that the frequency of $\lambda1$ is mismatched with the filtering frequency of the waveguide with Port B, $\lambda1$ is reflected back to the first resonator and tunnels into the transitional waveguide. Then, $\lambda1$ rotates into the waveguide with Port C after passing through the second resonator. The same situation as the waveguide with Port B, $\lambda1$ is reflected by the waveguide with Port C owing to the fact that the frequency of $\lambda1$ is mismatched with the filtering frequency, as well. At last, $\lambda1$ outputs from Port D. Similarly, $\lambda2$ and $\lambda3$ both output from Port D finally.

The field distribution of three frequencies excited from Port A is shown in Zhuang et al. (2016), which shows that most power of 193.4 THz transmits to Port B, 193.3 THz transmits to Port C, and 193.2 THz transmits to Port D. Channels 1–3 correspond to the frequencies of 193.4, 193.3, and 193.2 THz, respectively. The transmission spectrum of the multichannel multiplexer/demultiplexer when light is launched from Port A. The insertion loss of the frequencies 193.4, 193.3, and 193.2 THz is about 0.39, 0.48, and 0.42 dB, respectively. And the 1 dB bandwidth for Port B and Port C is about 10 and 12 GHz, respectively.

11.3 Design of Ring Resonator-Based 2D PC WDM Demultiplexer

Both the line and point defects are used to design a ring resonator in a 2D PC lattice. The size of the ring resonator is larger than the resonant cavity. It is used to enhance the signal strength inside the device, which reflects increasing transmission power in the output.

11.3.1 Ring Resonator-Based Heterostructure WDM Demultiplexer

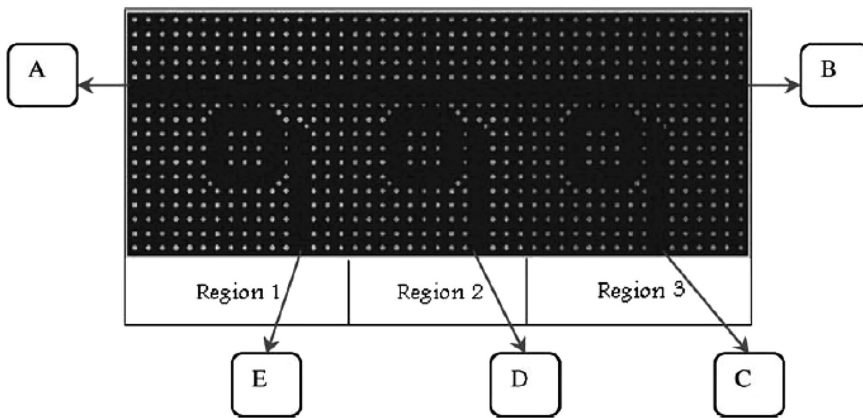
Djavid et al. (2008) reported a 2D PC WDDM heterostructure with four outputs. In [Figure 11.23](#), WDDM contains three regions 1, 2, and 3 with various refractive indexes of 3.82, 3.66, and 3.44, respectively. 2D PCs guide an electromagnetic wave propagating through different refractive index structures with minimal propagation losses.

The structures of regions 1, 2, and 3 have the following bandgap, respectively:

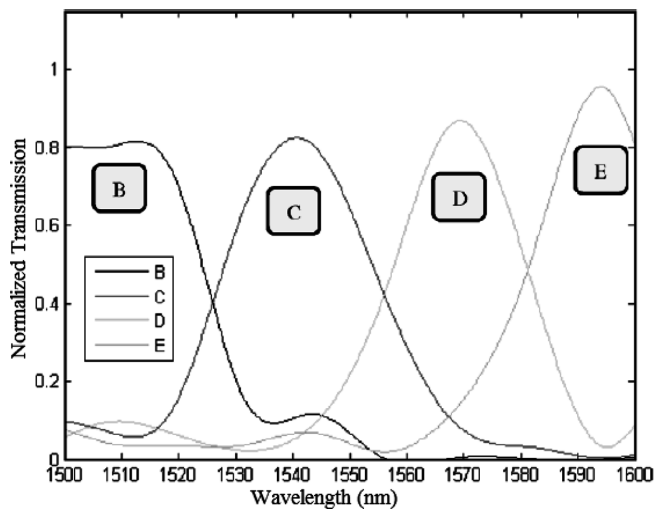
$0.2903 < a/\lambda < 0.4495$ —first region

$0.3010 < a/\lambda < 0.4544$ —second region

$0.3170 < a/\lambda < 0.4606$ —third region

**FIGURE 11.23**

Heterostructure WDDM with ring resonators. (From Djavid, M. et al., *Opt. Commun.*, 281, 4028–4032, 2008.)

**FIGURE 11.24**

Optical power transmission characteristics of four-output WDDM with ring resonator. (From Djavid, M. et al., *Opt. Commun.*, 281, 4028–4032, 2008.)

These regions depend on the parameters, such as r/a and dielectric constant. Hence, the equivalent bandgap is $0.3170 < a/k < 0.4495$. In this bandgap, incident wave is transmitted through the waveguide, which is gone through all regions without any reflection.

Five dropping ports of the structure are labeled as A, B, C, D, and E, as shown in Figure 11.23. The normalized transmission of the heterostructure WDDM is shown in Figure 11.24. Four different wavelengths at dropping ports B, C, D, and E are 1513, 1541, 1569, and 1594 nm. The normalized transmissions of these wavelengths are 82%, 83%, 87%, and 96%, respectively.

11.3.2 Quasi Square Ring Resonator-Based Three-Channel WDM Demultiplexer

Heterostructure four-channel wavelength demultiplexer using a square PC ring resonator is reported by Rakhshani and Mansouri-Birjandi (2012). The device is composed of three regions. The dielectric constants of left, middle, and right regions are 14.44, 12.96, and 11.56 of the demultiplexer, which is made by electro-optic (E-O) or thermo-optic (T-O) materials.

E-O materials are used to change their refractive indexes in response to an external electric field. The T-O effect caused by two-photon absorption (TPA) in Si to control the resonator's refractive index through the heat generated by optically produced carriers is used. The equivalent bandgap of the device is $0.288 < a/\lambda < 0.309$. In this equivalent bandgap, incident wave is transmitted through the waveguide going through all regions without any reflection. Four ports of the structure are labeled as A, B, C, and D, as shown in Figure 11.25.

Figure 11.26 shows the normalized transmission of the heterostructure demultiplexer. FDTD simulated results at four different wavelengths of dropping waveguides A, B, C, and D are $\lambda_1 = 1510$ nm, $\lambda_2 = 1544$ nm, $\lambda_3 = 1561$ nm, and $\lambda_4 = 1581$ nm. The normalized transmissions of these wavelengths are over 82%, 91%, 97%, and 90%, respectively. The crosstalk range is between -15 and -34 dB. The array size is 11.19×26.5 μm , and the average dropping efficiency is larger than 90%.

11.3.3 Wavelength Demultiplexer Based on Heterostructure PC Ring Resonator

In Rakhshani and Mansouri-Birjandi (2013), a square lattice of dielectric rods in air background has a dielectric constant of 12, radius of $r = 0.2a$, where $a = 540$ nm is a lattice constant. The bandgap of the structure with the normalized frequency of $0.2943 < a/\lambda < 0.4353$ for TM polarization. For improving the transmitted power to port B, the radius of adjacent and coupling rods is set to $r_{\text{coupling}} = 0.97r$ and $r_{\text{adjacent}} = 0.87r$, respectively, where r is the radius of other rods. As shown in Figure 11.27, the ring with four additional rods is named as scatterer rods, which is intended to decrease the effects of the counter propagating modes. At on-resonance, the field of the waveguide fully couples to the ring, whereas at off-resonance, it does not couple and continues to propagate through the top waveguide.

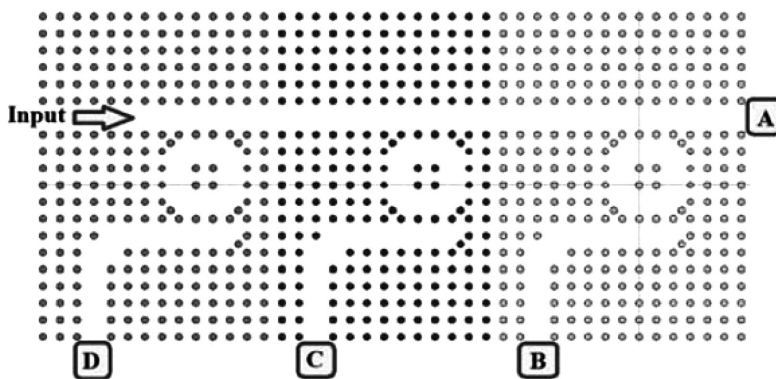
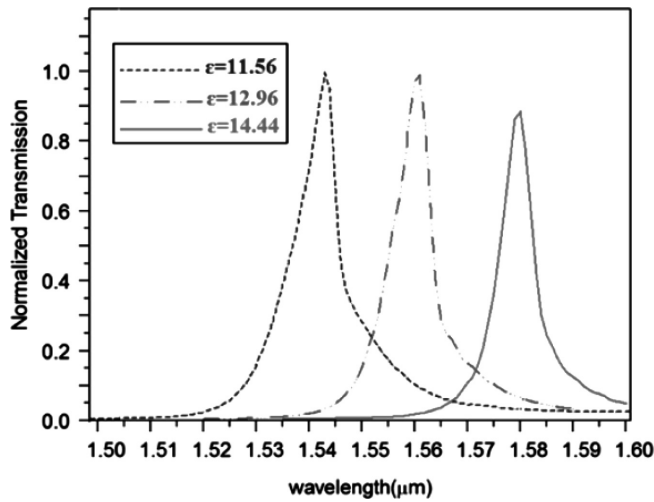
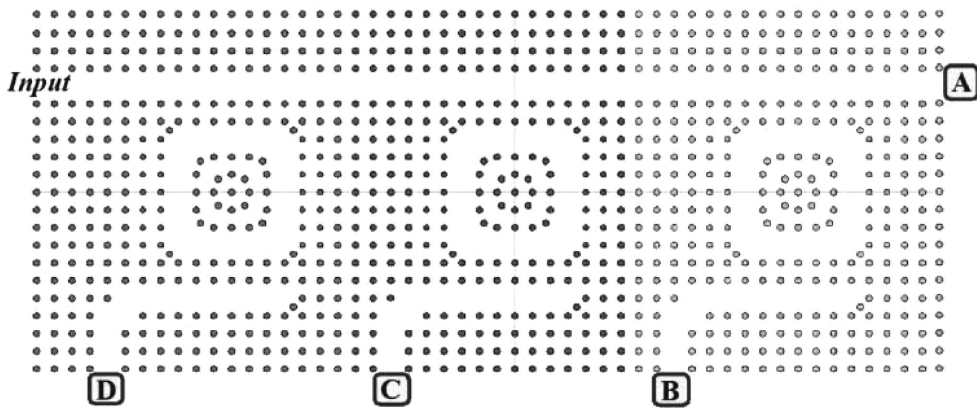


FIGURE 11.25

Three-channel WDM demultiplexer. (From Rakhshani, M.R. and Mansouri-Birjandi, M.A., *J. Electromagn. Waves Appl.*, 26, 1700–1707, 2012.)

**FIGURE 11.26**

Output spectrum of three-channel WDM demultiplexer. (From Rakhshani, M.R. and Mansouri-Birjandi, M.A., *J. Electromagn. Waves Appl.*, 26, 1700–1707, 2012.)

**FIGURE 11.27**

Wavelength demultiplexer based on the heterostructure photonic crystal ring resonator. (From Rakhshani, M.R. and Mansouri-Birjandi, M.A., *Physica E*, 50, 97–101, 2013.)

The device contains three regions with various dielectric constants as shown in Figure 11.29. The dielectric constants of left, middle, and right regions are 12.4, 12, and 11.6, respectively. Four dropping waveguides of the structure are labeled as A, B, C, and D.

Figure 11.28 shows the normalized transmission of the heterostructure demultiplexer. Four different resonant wavelengths at dropping output ports A, B, C, and D are $\lambda_1 = 1500$ nm, $\lambda_2 = 1510$ nm, $\lambda_3 = 1516.2$ nm, and $\lambda_4 = 1522.2$ nm, and the corresponding transmission powers at Port B, Port C and Port D are 92%, 95%, and 100%, respectively and Port A is acting as a dropping port.

Simulation results show that the crosstalk range is between -15 and -38 dB. The overall size of this structure is $294.25 \mu\text{m}^2$, and the average drop efficiency is larger than 95%.

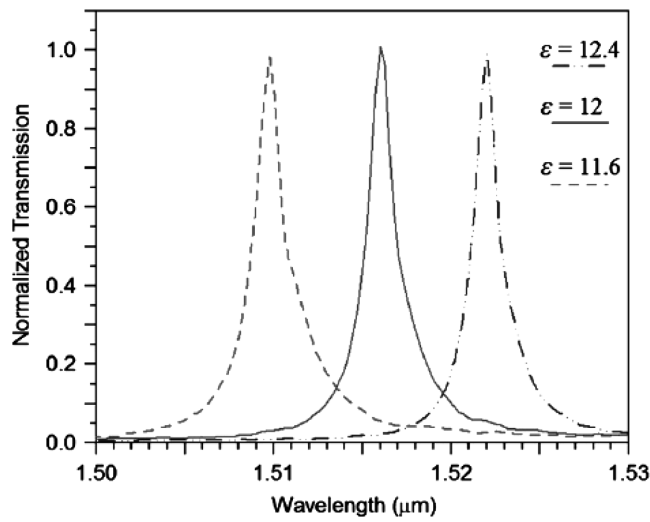


FIGURE 11.28

Output spectrum of wavelength demultiplexer based on the heterostructure photonic crystal ring resonator. (From Rakhshani, M.R. and Mansouri-Birjandi, M.A., *Physica E*, 50, 97–101, 2013.)

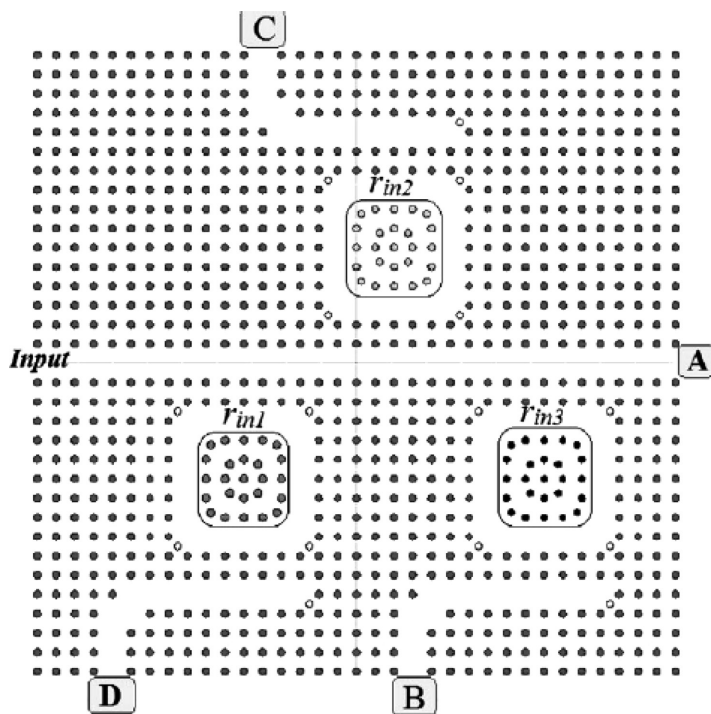


FIGURE 11.29

Tunable four-port wavelength demultiplexer. (From Mansouri-Birjandi, M.A. and Rakhshani, M.R., *Optik*, 124, 5923–5926, 2013.)

11.3.4 Tunable Four-Port Wavelength Demultiplexer

Mansouri-Birjandi and Rakhshani (2013) investigated PC ring resonator-based tunable four-port wavelength demultiplexer. In Figure 11.29, three rings have been used for the radius of the inner rods, wherein $r_{in} = 1.1r$ for the left ring, $r_{in} = r$ for the middle ring, and $r_{in} = 0.9r$ for the right ring, where r is denoted as the radius of other rods. Each ring has 5×5 ring resonator, based on the number of inner rods, in the square lattice of 2D PC. This structure is excited with TM polarization. The PBG range for this structure is in between normalized frequencies of $0.300 < a/\lambda < 0.435$. The four additional rods are named here as “scatterer.” These rods are used to decrease the effects of the counter propagating modes. For improving transmitted power to the dropping ports B, C, and D, the radius of adjacent and coupling rods is set to $r_{coupling} = 0.97r$ and $r_{adjacent} = 0.87r$ respectively, where r is the radius of other rods.

The normalized transmission spectrum in Figure 11.30 of this demultiplexer is obtained from 2D FDTD simulation. The device tunes three wavelengths at dropping ports B, C, and D, which are $\lambda_1 = 1507.8$ nm, $\lambda_2 = 1516.2$ nm, and $\lambda_3 = 1524.2$ nm with corresponding transmission efficiencies of 80%, 96%, and 95%, respectively.

In contrast, the remaining wavelengths enter into the port A. The channel spacing for this device is about 8 nm. The maximum power transmission at port C is about 96%, while the minimum power transmission at port B is about 80%. The Q has been calculated for the output channels valued at 390, 891, and 544 for the channels B, C, and D, respectively. The average crosstalk between the output channels is about -29 dB. The overall dimension of the device is about $317 \mu\text{m}^2$.

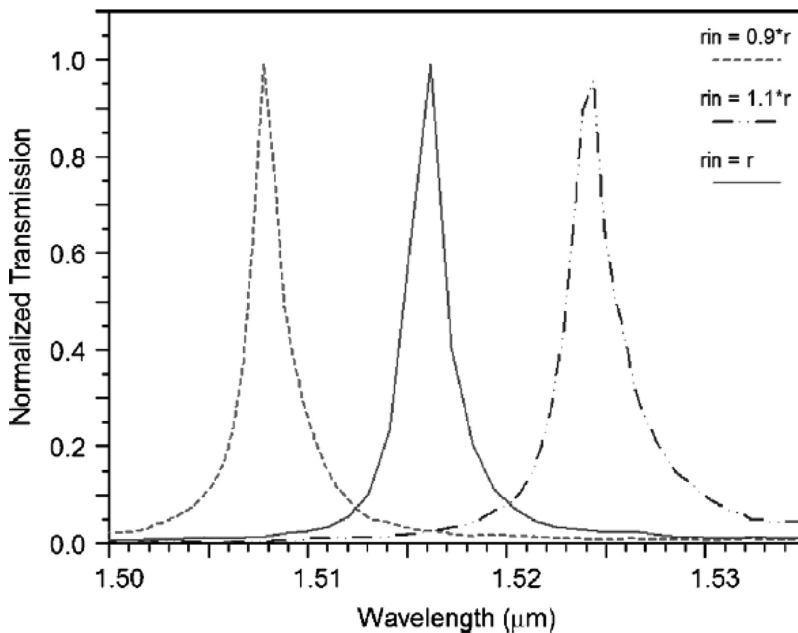


FIGURE 11.30

Output spectrum of tunable four-port wavelength demultiplexer. (From Mansouri-Birjandi, M.A. and Rakhshani, M.R., *Optik*, 124, 5923–5926, 2013.)

11.3.5 Square-Shaped Inner Array Cavity-Based Two-Channel All-Optical Demultiplexer

The Two dimensional PC ring resonator based two channel all-optical demultiplexer is reported by Ghorbanpour and Markouei (2013), which is a 40×35 square lattice of dielectric rods in air environment.

The refractive index and radius of dielectric rods are 3.49 and $0.2a$, respectively. The lattice constant of the 2D PC equals to 595 nm. Using the PWE method, it generates PBG, which is lying between 1451 and 2125 nm. The two-channel demultiplexer consists of one input waveguide in the center line of the structure, two dropping output waveguides in the upper and lower parts of the structure, respectively, and two resonant rings located between the input waveguides, and each output waveguide is shown in Figure 11.31.

The corner of each resonant ring is a scattering rod, which improves the resonant performance of the resonant rings. The lattice constant of the 5×5 structure is $0.95a$, and the radius of their dielectric rods in the upper and lower rings is $R_2 = 0.28a$ and $R_1 = 0.29a$, respectively. This different radius between the two rings and different resonant wavelengths of the structure can separate two different channels, and its central wavelengths are 1590.8 and 1593.8 nm with corresponding Q s 7954 and 3984; the crosstalk values of -22 and -11 dB separately are shown in Figure 11.32. The overall footprint of our proposed structure is $681.36 \mu\text{m}^2$.

11.3.6 Optical Wavelength Demultiplexer-Based PC Ring Resonator

Alipour-Banaei et al. (2015) reported the use of four-channel demultiplexer. The base of the structure is used by 2D PC with a square lattice, which is composed of dielectric rods in air background. The effective refractive index ($n = 3.6$) of dielectric material, radius ($r = 0.235a$) of dielectric rods, and lattice constant (equal to $a = 806$ nm) of 2D PC are essential parameters to develop the PBG, which is lying between $1,250 \text{ nm} < \lambda < 1,820 \text{ nm}$. The resonant ring is created by removing a 7×7 array of dielectric rods as shown in Figure 11.33. The radius of core rods is $0.235a$, where a is the lattice constant of the core structure and equals to $0.565a$.

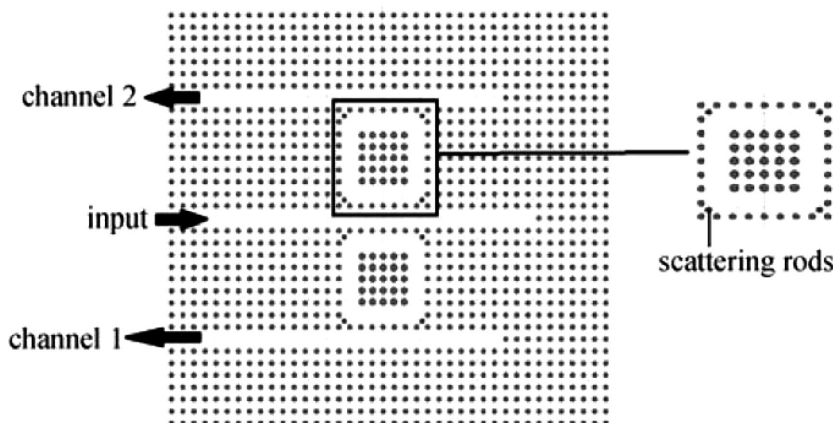
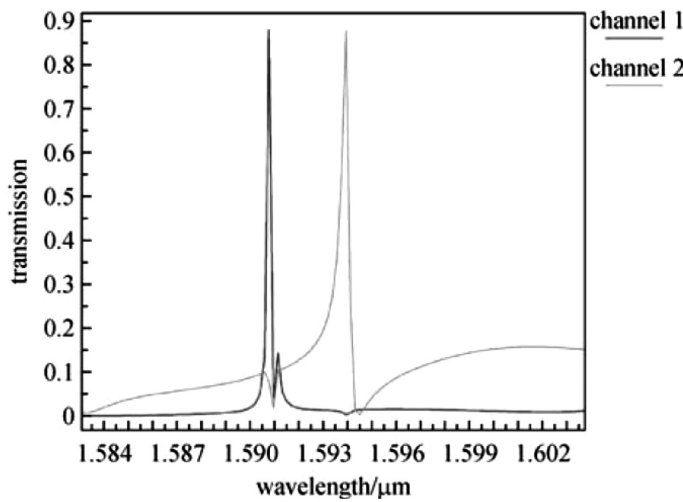
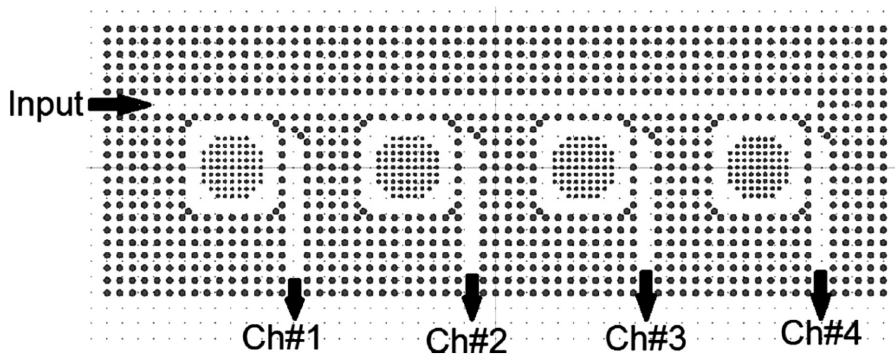


FIGURE 11.31

Two-channel all-optical demultiplexer. (From Ghorbanpour, H. and Markouei, S., *Optoelectron.*, 6, 224–227, 2013.)

**FIGURE 11.32**

Output spectrum of two-channel all-optical demultiplexer. (From Ghorbanpour, H. and Markouei, S., *Optoelectron.*, 6, 224–227, 2013.)

**FIGURE 11.33**

Optical wavelength demultiplexer based on the photonic crystal ring resonator. (From Alipour-Banaei, H. et al., *Photon. Netw. Commun.*, 29, 146–150, 2015.)

The 2D FDTD simulation is done during 20,000 time steps, which requires 426-min runtime and 45-MB memory size for this demultiplexer. The ring resonator mechanism selected four channels such as $\lambda_1 = 1,569.5$ nm, $\lambda_2 = 1,572.5$ nm, $\lambda_3 = 1,575.5$ nm, and $\lambda_4 = 1,577.5$ nm.

The output spectrum of the PCRR-based demultiplexer is shown in [Figure 11.34](#). The channel spacing and average bandwidth are 3 and 0.5 nm, respectively. The minimum transmission efficiency of the structure is 95%, and the overall Q is more than 2,600. The crosstalk of this structure varies from -19 to -40 dB.

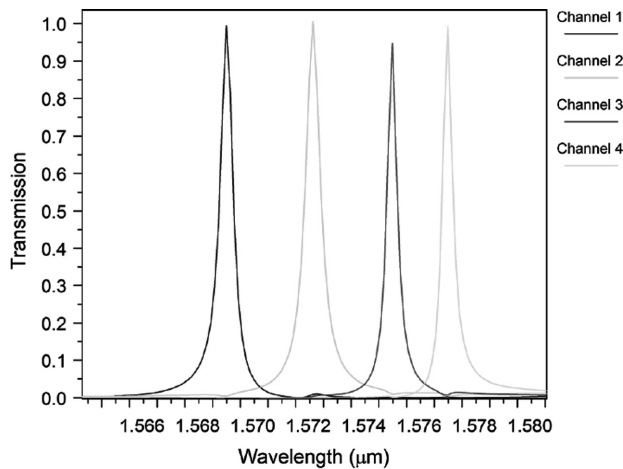


FIGURE 11.34

Output spectrum of optical wavelength demultiplexer-based photonic crystal ring resonator. (From Alipour-Banaei, H. et al., *Photon. Netw. Commun.*, 29, 146–150, 2015.)

11.3.7 Ring Resonator and Cavity-Based Three-Channel Wavelength Division Multiplexer

Zhang et al. (2015) reported a device on three-channel WDM based on a symmetrical coupling.

Figure 11.35 shows a reported device, which is composed of a 2D PC with a square lattice of Si rods in the air host. The lattice constant is $a = 560$ nm, the refractive index (n) of Si is 3.464, and the radius of Si rods is $r = 103$ nm. The PWE method is executed on the structure that generates PBG located in the normalized frequency (a/λ) region of 0.30–0.43 for TE polarization.

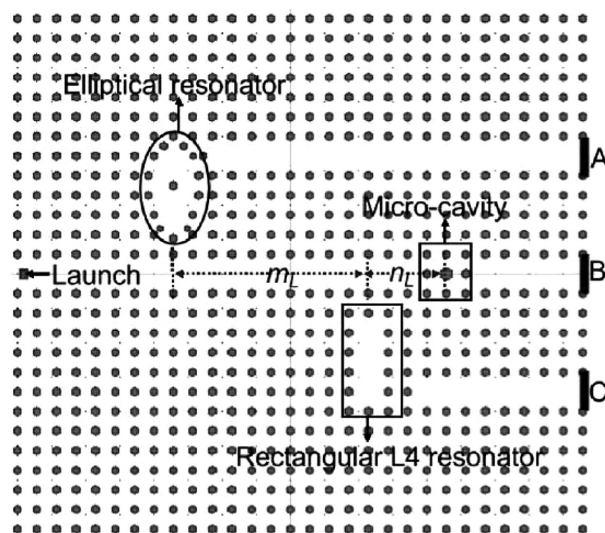
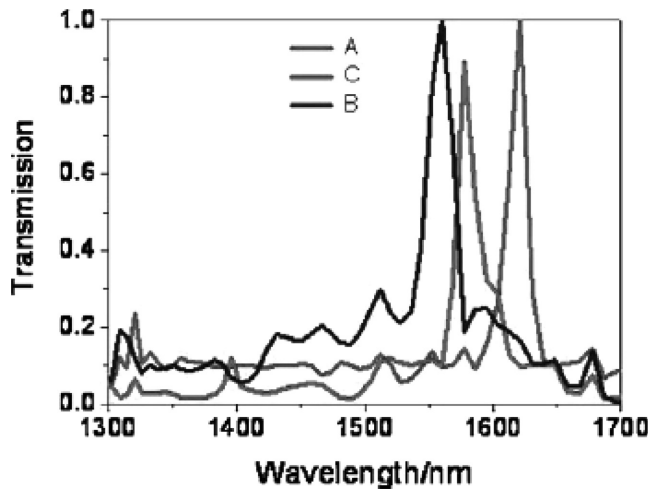


FIGURE 11.35

Three-channel wavelength division multiplexer. (From Zhang, X. et al., *Optik*, 126, 1138–1141, 2015.)

**FIGURE 11.36**

Output spectrum of three-channel wavelength division multiplexer. (From Zhang, X. et al., *Optik*, 126, 1138–1141, 2015.)

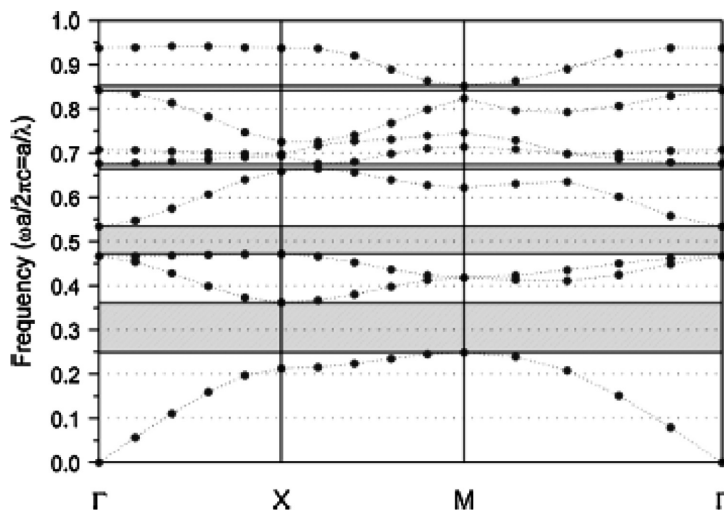
Three output ports are formed by removing one row of rods, which are labeled with A, B, and C, respectively. The elliptical cavity and the L4 cavity are designed by removing the dielectric rods to form corresponding shapes. A point defect microcavity is placed at the end of the bus waveguide by setting the radius of the middle rod to $1.5r$, which is used to couple the optical field from the input waveguide into the up and down output waveguides at the resonant frequencies.

By simulating this structure, three wavelengths of $\lambda = 1620$, 1560 , and 1580 nm are filtered in the dropping output ports A, B and C, respectively, as shown in [Figure 11.36](#). The normalized transmission intensity of these wavelengths is up to 100%, 90%, and 100%, respectively.

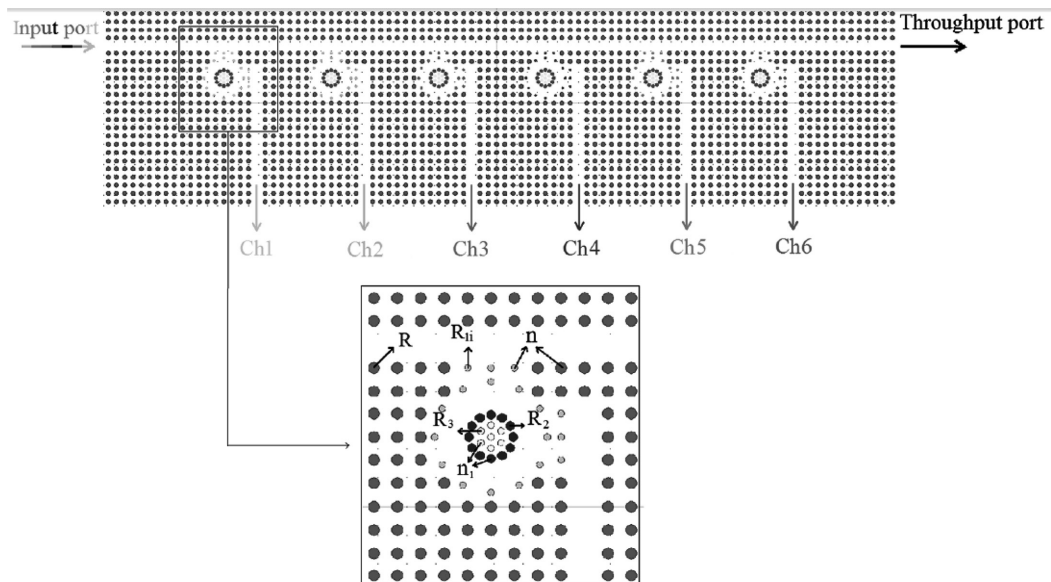
11.3.8 Circular Ring Resonator-Based Six/Eight-Channel Demultiplexer

Talebzadeh et al. (2017) reported multilayer ring resonator-based six- and eight-channel demultiplexers using Si/C rods. The refractive index (n), radius (r) of the silicon rods, and lattice constant (a) of the PCs are 3.48, 190 nm, and 800, respectively. The PWE calculates the PBG of a basic structure with silicon rods with a wavelength of 1550 nm. [Figure 11.37](#) shows that there are four PBG regions in the proposed structure. The second PBG obtained is from 1518 to 1712 nm and is suitable for optical communication systems.

The demultiplexers separate multiple adjacent optical channels according to their central wavelengths. A six-channel demultiplexer ([Figure 11.38](#)) uses six resonators whose resonant wavelengths differ from each other. The resonant wavelength of ring resonators depends on the structural parameters. Each ring resonator consists of a main ring and two interior layers; the refractive indices of the rods are equal to the refractive indices of the basic silicon rods ($n = 3.48$), and carbon rods are chosen for the interior rings so that their refractive indices are lower ($n_1 = 2.3878$) than that of the basic structure.

**FIGURE 11.37**

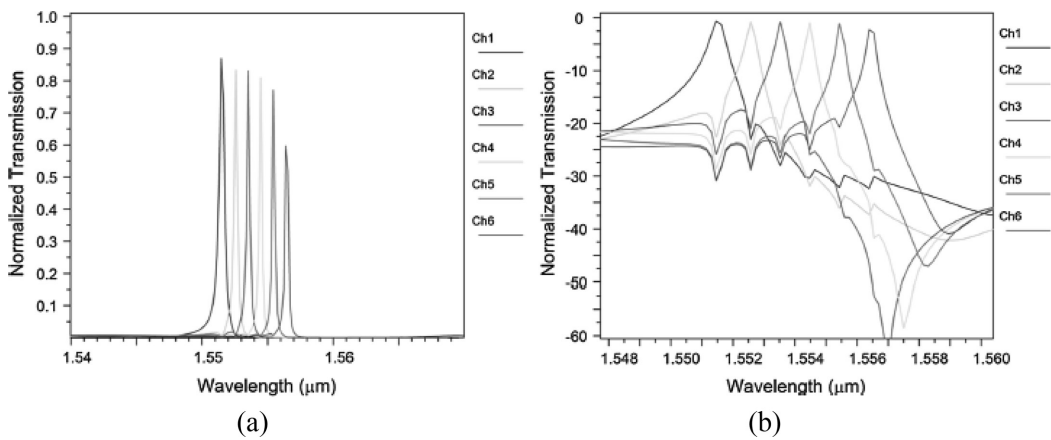
Band diagram of 2D PC structure before introducing defects. (From Talebzadeh, R. et al., *Photon. Netw. Commun.*, 34, 248–257, 2017.)

**FIGURE 11.38**

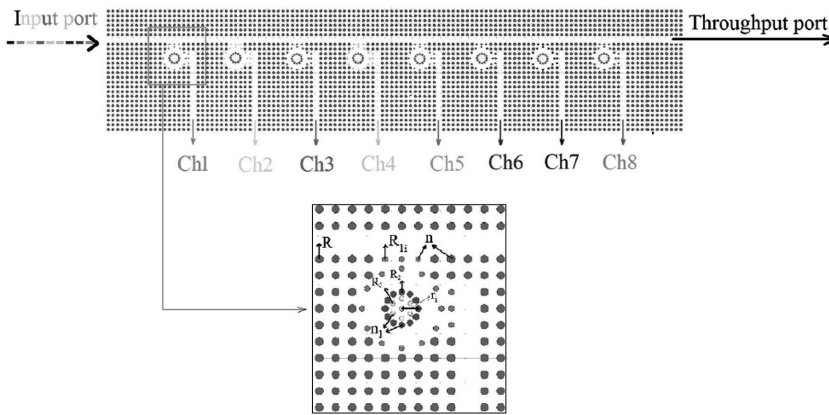
Schematic of six-channel demultiplexer. (From Talebzadeh, R. et al., *Photon. Netw. Commun.*, 34, 248–257, 2017.)

The radii of the dark magenta carbon rods for the interior layers are shown by $R_2 = 153$ nm, and the radii of the yellow rods are $R_3 = 115$ nm for all six rings. The rod radii of the six main silicon ring resonators are $R_{1i} = 80, 85, 90, 95, 100,$ and 105 nm.

Figure 11.39a and b presents the output spectrum of six-channel demultiplexer. The average Q of 3537, an average power transmission efficiency of 80%, and the minimum and maximum crosstalk values of -13.3 and -38.1 dB are shown in Figure 11.39.

**FIGURE 11.39**

Output spectrum of six-channel demultiplexer: (a) normal scale and (b) dB scale. (From Talebzadeh, R. et al., *Photon. Netw. Commun.*, 34, 248–257, 2017.)

**FIGURE 11.40**

Schematic of eight-channel demultiplexer. (From Talebzadeh, R. et al., *Photon. Netw. Commun.*, 34, 248–257, 2017.)

Figure 11.40 shows the structure of an eight-channel demultiplexer. Each interior ring is composed of 12 carbon rods. The distance between the center of each ring to the center of its rods is the radius of the ring, which is denoted by r_i . In this section, the index i vary from one to eight for the channels. The values of R_i are 100, 105, 110, 115, 120, 120, 125, and 125 nm for the eight main silicon rod rings, and the values of r_i are 800, 800, 800, 800, 800, 785, 800, and 755 nm for the interior carbon rod rings, respectively.

In Figure 11.41, it is shown that the minimum and maximum crosstalk values for the eight-channel demultiplexer are -11 and -47 dB, respectively. The difference between channels is set to be 1 nm. The average Q and transmission efficiency of 3716 and 91% were obtained, respectively.

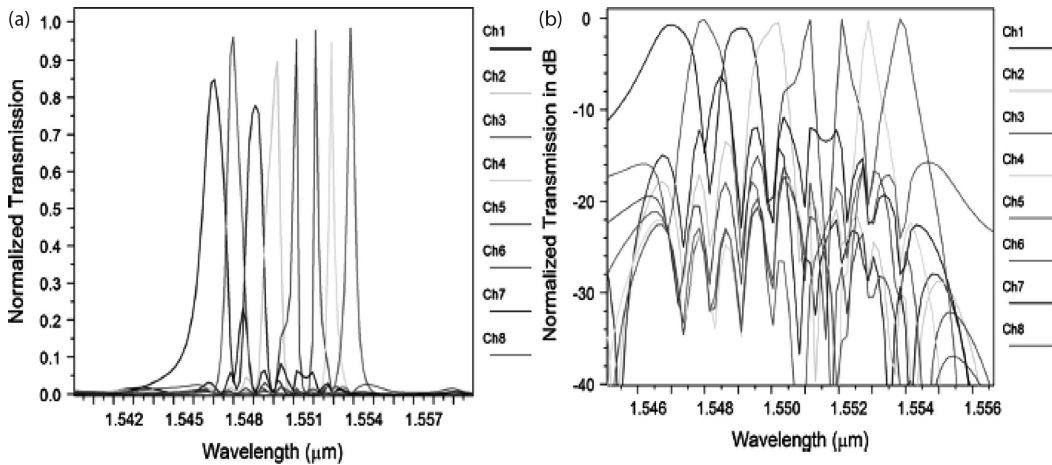


FIGURE 11.41

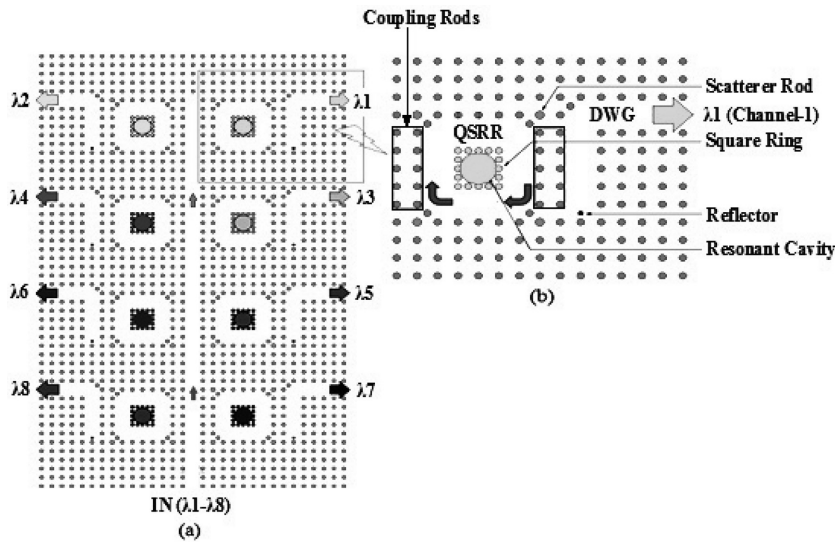
Output spectrum of eight-channel demultiplexer: (a) normal scale and (b) dB scale. (From Talebzadeh, R. et al., *Photon. Netw. Commun.*, 34, 248–257, 2017.)

11.3.9 Square Ring Cavity Inside the Quasi Square Ring Resonator-Based Eight Channel DWDM Demultiplexer

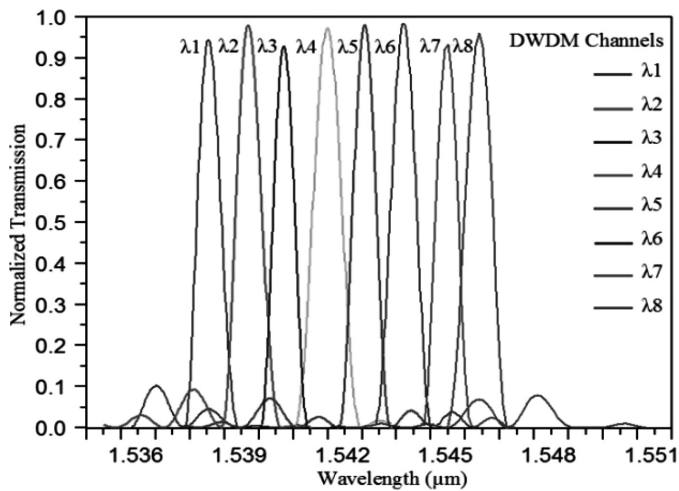
Venkatachalam et al. (2017) designed the parameters of the structure, and its PBG such as radius (r) of the dielectric rods is 100 nm, lattice constant (a) is 562 nm, and refractive index difference of the GaAs (Δ) is 2.24. The PWE evaluates that the PBG range is lying in between 0.32151 and 0.45174 (a/λ) whose corresponding wavelength range is 1244–1748 nm, which is attained by 31×50 arrays of dielectric rods with the overall size of $17.4 \times 28.2 \mu\text{m}$. Hence, the overall size of this proposed structure is $490.68 \mu\text{m}^2$.

Figure 11.42a and b shows structural and sectional views of the proposed eight-channel demultiplexer. The device consists of eight quasi square ring resonators (QSRRs) that are divided equally as odd and even number of ports in left and right sides of the bus waveguide. A rod with a radius of 500 nm is acting as a resonant cavity to select resonant wavelength, which is located inside each square ring of QSRR. The refractive index of resonant cavity in the QSRRs of proposed demultiplexer has 3.62, 3.64, 3.66, 3.68, 3.7, 3.72, 3.74, and 3.76, respectively. The corner of each quasi square resonator has a scatterer rod with 120 nm size, which is used to reduce the scattering beams, other than the signal traveling path of a proposed structure. The dropping waveguide (DWG) is located near the quasi square ring resonator in L shape. It has a reflector rod at the closed end L bend waveguide with 50-nm spacing. This is used to reflect the selected channel, and its dimensions are 70, 71, 72, 73, 74, 75, 76, and 77 nm of the various output ports. The two columns of coupling rods are placed in between bus waveguide and quasi square ring resonator and quasi square ring resonator and dropping waveguide. These rods are used to couple the light signal from bus waveguides to the quasi square ring resonator and then send to L bend waveguide.

Figure 11.43 shows a spectral response of proposed DWDM eight-channel demultiplexer. The FDTD simulation is used to perform the device function and study the resonance behavior of the proposed structure. The resonant wavelength range of DWDM demultiplexer is spanning from 1538.5–1546.4 nm, and the spacing between the channels approximately is 1.1 nm. From this paper, it is noticed that the refractive index-based resonant

**FIGURE 11.42**

(a) Schematic of proposed eight-channel demultiplexer and (b) a sectional view of ring resonator. (Venkatachalam et al. 2017)

**FIGURE 11.43**

Spectra outcomes of proposed eight-channel demultiplexer. (Venkatachalam et al. 2017)

cavity in QSRR eight-channel demultiplexer is designed and investigated the functional parameters of proposed DWDM demultiplexer. The refractive index of an inner rod is acting as a resonant cavity, which reflects the desired resonant wavelength of the DWDM channels. The normalized transmission efficiency, the Q factor, and the channel spacing of proposed demultiplexer are 96%, 2050, and 1.1 nm, respectively. Hence, the device is applicable to design photonic integrated circuit for DWDM device.

From Table 11.1, it is noticed that the Rostami et al. (2010, 2011) reported $536 \mu\text{m}^2$ sizes of the WDM demultiplexer using a triangular lattice for four channels with a narrow spectral width, channel spacing, transmission efficiency, the Q factor, and crosstalk of

TABLE 11.1
Comparison of Resonant Cavity and Ring Resonator-Based WDM Demultiplexer

Authors/Year	Lattice Structure	Dimension μm^2	Number of Channels (λ)	Spectral Width ($\Delta\lambda$) (nm)	Channel Spacing (λ_c) (nm)	Transmission Efficiency (η) (%)	Quality Factor (Q)	Crosstalk (X_{ij}) (dB)
<i>Resonant Cavity-Based WDM Demultiplexer</i>								
Rostami et al. (2010)	Triangular	536	4	0.5	0.8	58	4170	-18.77
Rostami et al. (2011)	Triangular	313.28	4	1	3.5	80	1496.7	-22.54
Zhang et al. (2011)	Triangular	156.25	2	***	180	97	***	***
Alipour-Banaei et al. (2013a)	Triangular	422.4	4	1.2	2.7	52	1234	-23.7
Alipour-Banaei et al. (2015)	Triangular	***	2	0.5	3	77	382	-16
Gupta and Janyani (2014)	Square	484	4	0.2	0.8	***	7800	***
Mehdizadeh and Soroosh (2015)	Square	495	8	0.7	19.5	96	2200	-11.2
<i>Ring Resonator-Based WDM Demultiplexer</i>								
Djavid et al. (2008)	Square	***	4	30	28	85	***	***
Rakhshani and Mansouri-Birjandi (2013)	Square	315	3	***	***	90	***	-25
Rakhshani and Mansouri-Birjandi (2012)	Square	294.25	3	2.75	6.1	95	567	-24.44
Mansouri-Birjandi and Rakhshani (2013)	Square	317	3	2.8	8	90	547	-29
Ghorbanpour and Markouei (2013)	Square	681.36	2	0.3	3	90	7954, 3984	-22
Alipour-Banaei et al. (2015)	Square	***	4	4	4.4	95	3409	-19
Mehdizadeh et al. (2016)	Square	***	4	1.4	3.2	92	1224	-18
Talebzadeh et al. (2017)	Square	2030	8	***	1.1	93	4320	-47
Venkatachalam et al. (2017)	Square	490.68	8	1.1	0.76	96	2050	-11.9

0.5 nm, 0.8 nm, 79%, 4170, and -21 dB, respectively. Zhang et al. (2011) reported a small size ($156.25 \mu\text{m}^2$) of two-channel demultiplexer with 180-nm channel spacing, and the transmission efficiency is about 97%. Alipour-Banaei et al. (2013b) designed resonant cavity-based seven-channel demultiplexer with $107.25 \mu\text{m}^2$ size, and the channel spacing of 27 nm and the low transmission efficiency of 41% were obtained. A resonant cavity-based four-channel demultiplexer was designed by Alipour-Banaei et al. (2013b), and all the performance parameters such as spectral width, channel spacing, transmission efficiency, the Q factor, and crosstalk were 1.2 nm, 2.7 nm, 52%, 1234, and -23.7 dB, respectively. The overall size of this device was about $422.4 \mu\text{m}^2$.

Djavid et al. (2008) designed a ring resonator-based four-channel demultiplexer using a square lattice, and the spectral width of 30 nm, the channel spacing of 28 nm, and the transmission efficiency of around 85% were obtained. A ring resonator-based three-channel WDM demultiplexer was designed by Rakhshani and Mansouri-Birjandi (2013), and the performance parameters such as 2.75 nm spectral width, 6.1-nm channel spacing, 95% transmission efficiency, lesser Q factor, and -24.44 dB crosstalk were obtained. Ghorbanpour and Markouei (2013) reported a ring resonator-based two-channel demultiplexer with a narrow spectral width of 0.3 nm and high Q factor of 7954 for Channel 1 and 3984 for Channel 2. Mansouri-Birjandi et al. (2013) reported a three-channel demultiplexer where the minimum crosstalk was about -29 dB. A resonant cavity-based four-channel demultiplexer (Gupta and Janyani 2014) was designed with a very narrow spectral width of 0.2 nm, spacing between the channels of nearly about 0.8 nm, and a high Q factor of 7800. Alipour-Banaei et al. (2015) reported four-channel demultiplexer using a square lattice. Mehdizadeh and Soroosh (2015, 2016) investigated four- and eight-channel demultiplexer and analyzed the performance parameters. Talebzadeh et al. (2017) reported eight-channel demultiplexer using the square lattice, and the obtained parameters were Q factor of 4320 and crosstalk of -47 dB.

From the above reported structures, it is noticed that the 2D PC triangular and square lattice resonant cavity and ring resonator-based demultiplexer were designed. The transmission efficiency of reported eight-channel demultiplexer was nearly about 96%, and the channel spacing was 19.5 nm from Farhad Mehdizadeh and Soroosh (2015) and 93% from Reza Talebzadeh et al. (2017). However, the overall size was 495 – $2030 \mu\text{m}^2$, respectively. Venkatachalam et al. reported WDM demultiplexer for eight channels, and the obtained mean wavelength, transmission, spectral width, channel spacing, Q factor, and crosstalk are 1543 nm, 96%, 0.76 nm, 1.15 nm, 2050, and -11.9 dB, respectively.

11.4 Conclusion

This chapter analyzed the performance of WDM demultiplexers, and its designs are based on the resonant cavity and the ring resonator. The fundamental structures are made from either 2D PC triangular lattice or square lattice. The shape of the resonant cavity and ring resonator plays an eminent role in designing demultiplexers. The resonant wavelength of the channels of demultiplexer is depending on the size or refractive index of rods/holes in a resonant cavity or ring resonator. The methods have distinct function, and its functional parameters such as resonant wavelength, spectral width, channel spacing, transmission efficiency, the Q factor, and crosstalk are investigated, and the overall size of the structure is also considered to develop photonic integrated circuits.

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12

Photonic Crystal-Based Logic Gates

Nirmala Maria D'souza and Vincent Mathew

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12.1 Introduction

Photonic crystals can play a prominent role in all-optic signal processing and computing. They have drawn significant attention toward the design of optical devices using their peculiar properties, in terms of power consumption, speed, and confinement of wave and their compactness. Various logic devices have been realized by implementing resonance, nonlinearity, and interference or self-collimation events, which include optical logic gates, optical switches, flip-flops, adders/subtractors, encoders/decoders, and inverters (Sukhoivanov 2009; Joannopoulos et al. 2011).

Optical logic gate is the key component in the optical signal processing circuits (Pereira et al. 2003; Zaghoul and Zaghoul 2006). Hence, various working principles were proposed (Houbavlis et al. 1999; Notomi et al. 2007; Soto et al. 2002; Zhao et al. 2007). They are mainly grouped into two based on the usage of nonlinear materials. They can be further classified into ring resonator-based structures, interference-based waveguides, and self-collimated beam-controlled devices based on the mechanism of operation. Among these, the first two structures require a photonic bandgap for the device to become functional, and the introduction of defect decides the operating frequency within the photonic bandgap. However, for the third structure, the photonic bandgap is not necessary. They are working based on the self-collimation effect (Zhang et al. 2007). The collimation is obtained by strong dispersive nature of photonic crystal and is usually independent of light intensity (Salmanpour et al. 2015).

Each of the above discussed classes of optical logic gate has their own merits and demerits. The gates based on bandgaps can operate with high-speed and low-power consumption. The self-collimated device provides a wide range of operating wavelength, and the

beam inside the photonic crystal is insensitive to the incident light. However, they should maintain a minimum size in order to obtain the self-collimation effect. Certain gate structures with nonlinear materials may consume high power, which makes them less useful (Salmanpour et al. 2015).

This chapter discusses some examples for all-optical logic gate design, working on the interference phenomenon. The interference-based photonic crystal devices are favorable, where the nonlinear materials are not used. However, interference-based structures are limited, due to their difficulty in precisely controlling the phase-shift difference for all input signals (Andalib and Granpayeh 2009). To obtain high intensity, contrast between logic states of one and zero is also difficult (Zhu et al. 2006). There are some optical logic gates based on the interference, which uses external phase shifters for their operation. However, this causes inconvenience and also requires additional components (Ishizaka et al. 2011; Liu et al. 2013).

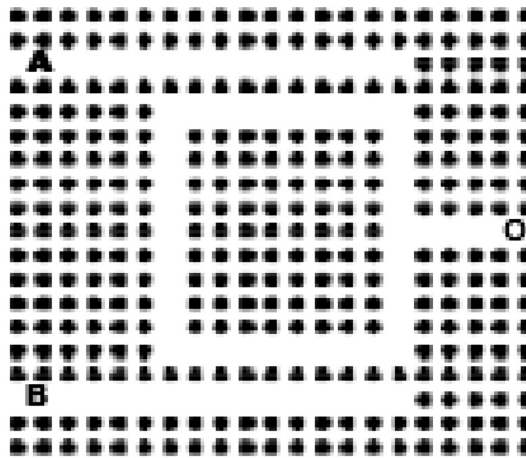
Most of the interference-based optical logic gates use a triangular photonic crystal lattice (Ishizaka et al. 2011; Liu et al. 2013). However, in this chapter, optical logic gates using a new type of structure on a square lattice photonic crystal platform are discussed. The square lattice provides the effective confinement of light. The fabrication also becomes easier due to its simple geometry (Robinson and Nakkeeran 2012). The external phase shifters are also avoided and thus make convenient for applications. Nonlinear materials are not included, and hence it can operate with low-power signals and can also be operated with multiple wavelengths. The size of the presented devices is small and has a simple structure, which helps in designing optical integrated circuits.

In the following section, we provide a basic design of photonic crystal logic gate, based on which the principle of operation is discussed. A detailed investigation on the design shall then be attempted, which invariably involves the band structure calculation of the photonic crystal. Various logic gates are then discussed, and we demonstrate their operation using simulation results (D'souza and Mathew 2016a, 2016b).

12.2 Principle of Operation

The schematic representation of a typical photonic crystal-based logic gate is given in [Figure 12.1](#). The proposed device is composed of a square ring-resonator waveguide with three other linear waveguides, which are connected to each other by this ring-resonator waveguide. One of the three linear waveguides serves as output waveguide with output port O, and the remaining two waveguides are considered as input waveguides with input ports A and B, as shown in [Figure 12.1](#). These waveguides are obtained by removing the arrays of dielectric rods from the perfectly periodic structure of this two-dimensional photonic crystal. The dielectric rods are made of silicon with dielectric constant 11.56 and a radius of $r = 230$ nm. The period of lattice of this photonic crystal is $a = 650$ nm. The upper and lower sides of the square ring resonator waveguide are directly coupled to the two input waveguides, with a line of dielectric rods between each side and the corresponding input waveguide. The output waveguide is connected to the right side of the square ring resonator waveguide.

Considering the case of establishing the signal into either input port A or B, it can be split into two with different intensities, one that travels in clockwise and the other that travels in anticlockwise direction in the ring-resonator waveguide. These two light signals interfere

**FIGURE 12.1**

The design of optical logic gate on the photonic crystal.

at output waveguide and give variation of intensity at the output port O. Depending on whether they interfere constructively or destructively, the corresponding logic output is designated as 1 or 0 at the output port O. In these devices, it is very difficult to achieve a completely constructive or destructive interference due to difficulty in precise control of the phase difference, which is called a partial constructive or destructive interference. Hence the logic states 0 and 1 are distinguished by some threshold values.

In order to obtain the various optical logic gate functions, different phase variations are introduced by precisely controlling the path difference. A phase difference of π is produced when there is a path difference of one period between the waves (Fu et al. 2013). While analyzing different logic functions, the structural parameters are adjusted so that there will be a phase difference of odd or even integral multiple of π between the beams, which give a destructive or constructive interference.

The performance of various optical logic gates can be analyzed by calculating what is known as a contrast ratio (CR). It is a mathematical expression involving values of power output at different logic states, which is given as follows (Tang et al. 2014):

$$CR = 10 \log_{10} \frac{P_1}{P_2}, \quad (12.1)$$

where P_1 and P_0 are values of output power for the logic state 1 (corresponding to the maximum power output) and 0 (referred to the minimum power output), respectively.

12.3 Band Structure Calculations

The band structure calculation is actually an examination of all the dispersion properties $\omega(k)$ of the photonic crystal (Ho et al. 1990). In the case of homogeneous material, the wave vector is directly proportional to frequency and gives a linear relation between ω and k .

However, in the case of materials with a periodic refractive index, the frequency-wave vector graph shows bands with bandgaps, similar to the electron band structure of semiconductor (Sukhoivanov 2009). Symmetry of the periodic arrangement allows us to depend on the concepts of Brillouin zone, which simplifies the band structure calculations. The complexity of the band structure varies with the dimension of the crystal.

The plane wave expansion (PWE) method is one of the main computational methods used for the calculations of band structure of a photonic crystal. PWE method involves the computational calculations of eigenvalues, and the corresponding eigenvectors of Helmholtz equation formulated for a particular periodic structure, using the Bloch theorem and the Fourier series expansions of eigenfunctions (Sakoda 2004).

The behavior of electric and magnetic fields inside a photonic crystal, when an electromagnetic wave is incident on it, is influenced by macroscopic Maxwell's equations (in 1863). Electromagnetic wave propagating through the isotropic, nonmagnetic, and nonconductive media satisfies the following equations written in SI units (Jackson 1999):

$$\nabla \cdot \mathbf{B} = 0 \quad (12.2)$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \quad (12.3)$$

$$\nabla \cdot \mathbf{D} = 0 \quad (12.4)$$

$$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = 0. \quad (12.5)$$

The electric field $\mathbf{E}$ and the electric flux density $\mathbf{D}$ are related by the expression.

$\mathbf{D}(\mathbf{r}) = \epsilon_0 \epsilon_r \mathbf{E}(\mathbf{r})$ and the magnetic flux density $\mathbf{B}$ and magnetic field $\mathbf{H}$ satisfy the relation $\mathbf{B}(\mathbf{r}) = \mu_0 \mu_r \mathbf{H}(\mathbf{r})$. Here ϵ_0 and ϵ_r are the permittivity of the vacuum and relative permittivity of the nondispersive media, respectively. The vacuum permeability and relative magnetic permeability are μ_0 and μ_r , respectively. It is assumed that the medium is nonmagnetic, that is, $\mu_r = 1$.

All the quantities in equations (12.2) through (12.5) are functions of time and space. Thus the field inside the Maxwell's equations can be written as the product of time-dependent part and independent part as follows:

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r}) e^{-i\omega t} \quad (12.6)$$

$$\mathbf{B}(\mathbf{r}, t) = \mathbf{B}(\mathbf{r}) e^{-i\omega t}, \quad (12.7)$$

where ω is the frequency of the electromagnetic wave. Substituting these into the above equation and rearranging, we obtain the following:

$$\frac{1}{\epsilon(\mathbf{r})} \nabla \times (\nabla \times \mathbf{E}(\mathbf{r})) = \left(\frac{\omega}{c} \right)^2 \mathbf{E}(\mathbf{r}) \quad (12.8)$$

$$\nabla \times \frac{1}{\epsilon(\mathbf{r})} \nabla \times \mathbf{H}(\mathbf{r}) = \left(\frac{\omega}{c} \right)^2 \mathbf{E}(\mathbf{r}), \quad (12.9)$$

where c is the velocity of the light in vacuum. These are the eigenvalue equations with eigenoperators $\nabla \times \frac{1}{\varepsilon(r)} \nabla \times$ and $\frac{1}{\varepsilon(r)} \nabla \times (\nabla \times)$ and eigenfunctions $H(r)$ and $E(r)$ having eigenvalue $(\frac{\omega}{c})^2$ and are called the Helmholtz equations (Sakoda 2004).

These equations are solved for electric and magnetic fields, in order to determine the propagating modes inside the photonic crystals, which are scale invariant. Hence the solution at one length scale is used to determine the solution at any other scale. Thus in the band structure, frequencies are normalized by the period of the lattice, which is used in tailoring the optical properties of photonic crystals and in determining the operating frequency range for different photonic crystal-based device applications (Sakoda 2004, Joannopoulos et al. 2011).

Solving the Helmholtz equation for the photonic crystal is needed to determine its band structure using the PWE method. The problem consists of finding the eigenvalues corresponding to the eigenvector of this equation for the particular periodic structure. As it is difficult to solve this equation for an infinitely periodic structure, some approximation methods were used. The Bloch theorem is used to represent the infinite and periodic eigenfunction, according to which an eigenfunction inside the infinite periodic medium can be written as a multiplication of a plane wave and a periodic function having a periodicity of the lattice (Sukumar and Pask 2009). Using the Bloch theorem, the eigenfunction is represented as follows:

$$E(r) = E_{kn}(r) e^{-i\omega t} \quad (12.10)$$

$$B(r) = B_{kn}(r) e^{-i\omega t}, \quad (12.11)$$

where $E_{kn}(r)$ and $B_{kn}(r)$ are the periodic functions representing the wave vector k with state n . This function satisfies the following relation as follows:

$$E(r+a) = E(r) \quad (12.12)$$

$$H(r+a) = H(r), \quad (12.13)$$

where a is the lattice vector. The periodicity of the function allows their Fourier expansion of fields over the reciprocal lattice vectors. Thus all the periodic functions can be represented in terms of wave vectors in reciprocal space:

$$E_{kn}(r) = \sum_G E'_{kn}(G) e^{j(k+G) \cdot r} \quad (12.14)$$

$$H_{kn}(r) = \sum_G H'_{kn}(G) e^{j(k+G) \cdot r}, \quad (12.15)$$

where G is the reciprocal lattice vector. Here the dielectric function is a periodic one and also be expanded over reciprocal lattice. The reciprocal of dielectric function appears in the Helmholtz equations, which is expanded as follows:

$$\frac{1}{\varepsilon(r)} = \sum_G \chi(G) e^{j(k+G) \cdot r}, \quad (12.16)$$

where $\chi(G)$ is the Fourier expansion coefficient and depends on the reciprocal lattice vectors. Substituting all the above equations in the Helmholtz and solving, we obtain the following:

$$-\sum_{G'} \chi(G-G')(k+G') \times (k+G') \times E_{kn}(G') = \frac{\omega_{kn}^{(E)2}}{c^2} E_{kn}(G) \quad (12.17)$$

$$-\sum_{G'} \chi(G-G')(k+G') \times (k+G') \times H_{kn}(G') = \frac{\omega_{kn}^{(H)2}}{c^2} H_{kn}(G). \quad (12.18)$$

These are known as the master equations for a three-dimensional photonic crystal. In order to obtain the bands, we have to compute the eigenvectors and corresponding eigenvalues of this equation.

Figure 12.2a shows the square lattice arrangement of photonic crystal with dielectric rods of dielectric constant ε_a in air medium of dielectric function ε_b . The reciprocal of the corresponding lattice is shown in Figure 12.2b. The shaded gray square region within Figure 12.2c represents the Brillouin zone of the selected structure. The irreducible Brillouin zone defined by the black triangular portion ΓXM , within the Brillouin zone. The Γ , X , and M are constituting the symmetric points within the Brillouin zone followed from the group theory. They can be introduced as follows:

$$\Gamma = \frac{\pi}{a} [0,0] \quad (12.19)$$

$$M = \frac{\pi}{a} [0,1] \quad (12.20)$$

$$X = \frac{\pi}{a} [1,1], \quad (12.21)$$

where a is the lattice constant or period of the photonic crystal lattice. The band structure is determined only for these points of the irreducible zone, where it is supposed that maxima and minima of bands fall at these positions. Later, the band structure will be extended to the region outside the Brillouin zone using the symmetry of the structure.

The filling fraction for the square lattice is given as follows:

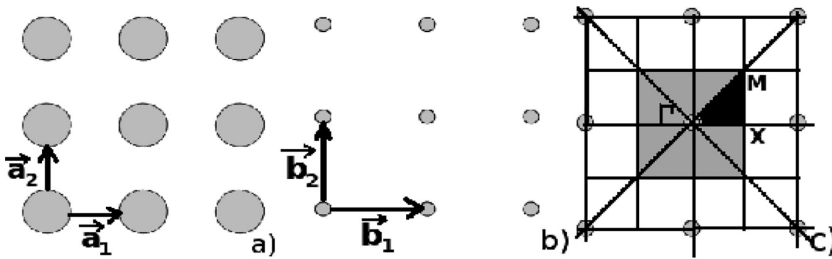
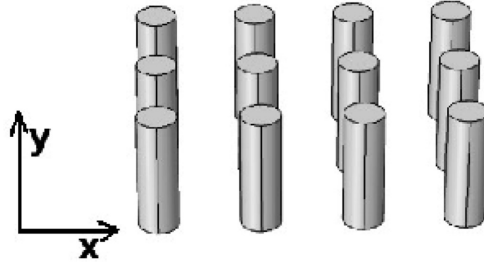


FIGURE 12.2

The schematic of real square lattice (a), its reciprocal lattice (b), and the corresponding Brillouin zone (c).

**FIGURE 12.3**

The schematic of the two-dimensional square lattice of dielectric rods in air medium.

$$f = \pi \left(\frac{r^2}{a^2} \right), \quad (12.22)$$

where r is the radius of the rods. Figure 12.3 shows the square lattice of silicon rods in air medium in x - and y -directions. The selected silicon has a radius of $r = 230$ nm and a dielectric constant 11.56. Here the lattice constant is $a = 650$ nm.

While investigating the propagation of electromagnetic radiation in a device like two-dimensional photonic crystals, two different polarizations are considered. They are S-polarization Transverse Electric (TE) and P-polarization Transverse Magnetic (TM), which will result in two different sets of equations. Here, only TM mode is considered, which has nonzero E_z , H_x , and H_y components. The master equation corresponding to the TM mode for the 2D photonic crystal can be written as follows:

$$-\sum_{G_{||}} \chi(G_{||} - G'_{||}) (k_{||} + G'_{||})^2 E_{zk_{||}n}(G'_{||}) = \frac{\omega_{kn}^{(E)2}}{c^2} E_{zk_{||}n}(G), \quad (12.23)$$

where $k_{||}$ represents wave vector and $G_{||}$ corresponds to lattice vectors in two dimensions.

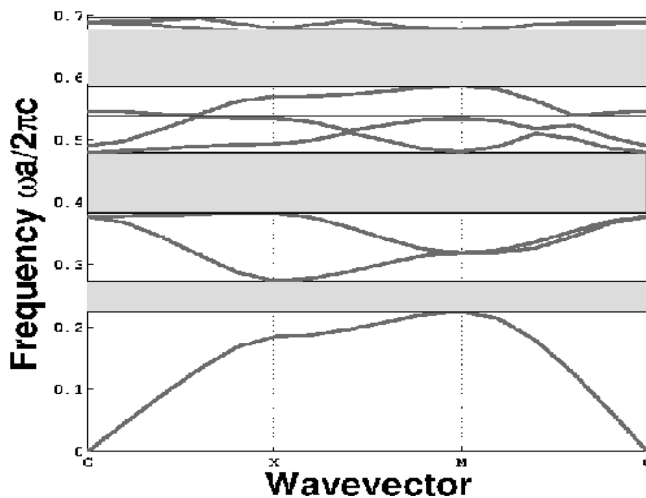
The following expression gives the coefficient of Fourier expansion of dielectric function of the considered structure:

$$\chi(G_{||}) = \frac{1}{V_0^2} \int_{V_0^2} \frac{1}{\varepsilon(r_{||})} e^{(-jG_{||} r_{||})} dr_{||}. \quad (12.24)$$

Here V_0^2 is the two-dimensional volume of the considered unit cell of the lattice. The $||$ label implies the consideration of the variables in the plane of photonic crystal only, and $r_{||}$ is the vector in the plane (x, y).

The above equation with two-dimensional square arrangements of rods with dielectric constant ε_a in air with permittivity ε_b takes the form as follows:

$$\chi(G_{||}) = \begin{cases} \frac{1}{\varepsilon_b} + f \left(\frac{1}{\varepsilon_a} - \frac{1}{\varepsilon_b} \right) & \text{for } G_{||} = 0 \\ 2f \left(\frac{1}{\varepsilon_a} - \frac{1}{\varepsilon_b} \right) \frac{J_1(G r_{||})}{G r_{||}} & \text{for } G_{||} \neq 0 \end{cases}. \quad (12.25)$$

**FIGURE 12.4**

The band structure diagram for 2D photonic crystal.

Using the PWE method, the dispersion has been plotted for TM mode, and it is shown in Figure 12.4 for the 2D square lattice photonic crystal. The photonic crystal has an arrangement of dielectric rods in air. A wavelength region of 1354–1706 nm corresponding to the bandgap at lower frequency region among the different available photonic bandgaps is selected. The band structure will give the information about the photonic bandgap of the photonic crystal, from which the operating wavelength region of the designed device is explored.

12.4 Simulation Method

In the previous section, we have discussed how the band structure is computed using the PWE method. As we have mentioned earlier, the band structure, and especially the bandgaps, is important in designing various logic gates. Now the task is to simulate the wave propagation through various proposed structures for assessing the performance of logic gates. For this purpose, we have used a finite difference time domain (FDTD) method, a method used often in photonics. The open source software MEEP was used for calculating FDTD (Taflov and Hagness 2000).

In simulation, Gaussian light with the center of frequency and width $0.42965 c/a$ and $0.1009 c/a$ (a is the lattice constant of the photonic crystal), respectively, is used as a source. In order to obtain particulars of power transmission in the device, continuous light sources were used, whose frequency is calculated using the information of field transmissions. The FDTD simulation domain has a dimension of $53950 \times 53950 \text{ nm}^2$, which has 13-nm grid spacing. We have used perfectly matched layers (PMLs) of thickness $10a$ at the domain border's act as periodic boundary conditions. In a PML technique, a layer with definite thickness and with carefully graded electric and magnetic conductivities is implemented at the boundaries of the computation space and is made to absorb the outgoing

waves via forcing the field amplitude to decay. As the name PML implies, there occurs a “perfect matching” of impedances of computation domain and PML, which leads to the complete removal of reflection at the interfaces (Taflov and Hagness 2000).

12.5 Discussion of Logic Operations

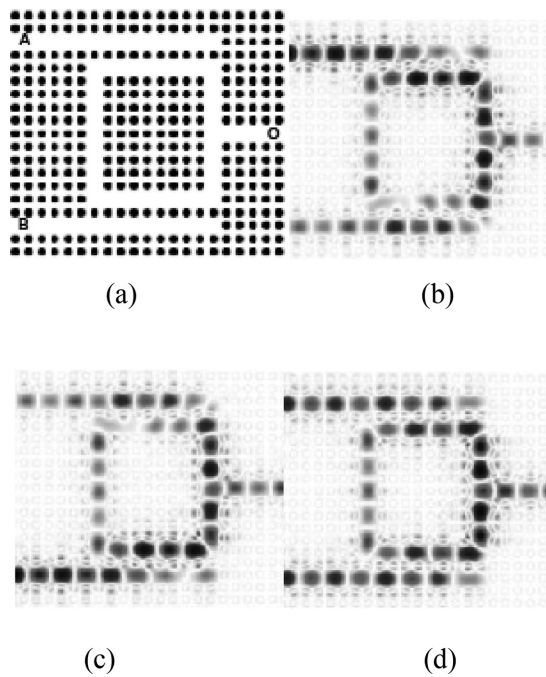
The different logic functions corresponding to various logic devices are discussed in the following sections, which consist of OR, NOT, AND, and XOR gates. The effects of changing the contact ratio and dielectric rod radius will be discussed (D’souza and Mathew 2016a, 2016b).

12.5.1 “OR” Logic Function

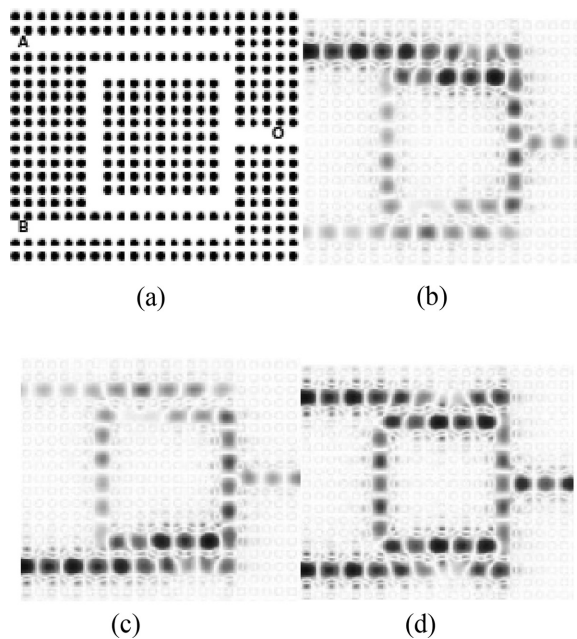
The optical OR gate is one that gives logic state zero only when both inputs were zero or else it will give logic state 1 for all the other input combinations. The photonic crystal design of the optical OR gate is shown in [Figure 12.5a](#). In order to obtain the OR logic function, the device is made of different waveguides by removing the dielectric rods. There are three linear waveguides that serve for the input and output signal propagations. The electric field profile is observed for the different logic function and is also shown in [Figure 12.5b–d](#). These different field distributions correspond to the same frequency of operation. In order to achieve this, first, the signal is applied to the port A only and is traveled through one of the input waveguides and splits at the rectangular waveguide into two with different intensities. From then, these two signals managed to reach the output waveguide through the ring waveguide. At the output, these signals interfere and give a partial constructive interference due to a phase difference between them, which occurred as a result of different paths they have traced. Thus we have obtained logic state 1 corresponding to the higher output than the particular determined value, which may refer to the logic function “1 OR 0 gives 1” and is shown in [Figure 12.5b](#). Similarly, we can also explain the case of where signal only applied to the port B, and this will give logic function “0 OR 1 gives 1” as shown in [Figure 12.5c](#). If a signal is simultaneously applied to the input ports A and B, then also there will be a higher output resulting in a logic state 1, as shown in [Figure 12.5d](#), which can be observed as logic operation “1 OR 1 gives 1.” Since, there is no signal applied to the case of “0 OR 0,” we have only 0 as output. From this, we can say that this particular optical device can resemble the electronic OR logic gate with a threshold value $>60\%$ for logic state 1 and $<5\%$ for logic state 0.

12.5.2 “AND” Logic Operation

The structure of OR gate is slightly modified in order to realize the AND logic operations. The new structure is shown in [Figure 12.6a](#). Considering the case of signal is applied for any one of the inputs either A or B, there will be a lower output resulted by the partial destructive interference between the waves. This lower output indicates the logic state 0, and the corresponding logic function is considered as “1 AND 0 gives 0,” which is shown in [Figure 12.6b](#). The similar “0 AND 1 = 0” logic operation is shown in [Figure 12.6c](#). The situation completely changes when signal is given to A and B simultaneously, which leads to an effective constructive interference developing a higher output analogous to logic state 1, referred to logic operation “1 AND 1 gives 1.” This operation is shown in [Figure 12.6d](#). Here the selected threshold values are $>90\%$ for the logic state 1 and $<50\%$ for the logic state 0.

**FIGURE 12.5**

(a) The OR gate design with the field profile analogous to the different OR logic gate functions, (b) corresponds to the logic function " $1 \text{ OR } 0 = 1$," (c) presents " $0 \text{ OR } 1 = 1$," and (d) gives " $1 \text{ OR } 1 = 1$."

**FIGURE 12.6**

(a) The AND gate design with the field profile analogous to the different AND logic gate functions, (b) gives " $1 \text{ AND } 0 = 0$," (c) presents " $0 \text{ AND } 1 = 0$," and (d) shows " $1 \text{ AND } 1 = 1$."

12.5.3 “XOR” Logic Operation

The structure of OR gate is further modified to give another logic function, that is, XOR gate as shown in [Figure 12.7a](#). In the new structure, one input wave guide is slightly shifted from the vertical symmetric position, so that there will be a large difference in phase between the two different traveling signals when applied simultaneously to A and B. [Figure 12.7b–d](#) shows the distinct logic operations of XOR gate. Thus when signal is applied to both A and B, we get a completely destructive interference, which will result in a logic operation of “1 XOR 1 = 0” ([Figure 12.7b](#)). Next, when the radiation is injected into the port either A or B only, the constructive interference between the waves resulted in a larger output. This is then designated to the logic operation “1 XOR 0 = 1” or “0 XOR 1 = 1” and is shown in [Figure 12.7c](#) and [d](#). Here, the transmittance >45% is referred to as logic state 1 or <5% as logic state 0.

12.5.4 “NOT” Optical Logic Function

Using the structure of XOR gate itself, a NOT gate logic function is also realized by choosing the input A as reference R ([Figure 12.8a](#)). The field corresponding to various logic operations of NOT optical gate is given in [Figure 12.8b–d](#). A wave will be always there in R, which will give a output corresponding to logic state 1 when no signal is given to the other port. This refers to the logic operation of “0 NOT=1,” as shown in [Figure 12.8b](#). However, if a signal is applied to the port B with R, then there will be a destructive interference between the two waves that result in a lower logic state 0 as shown in [Figure 12.8c](#). The threshold condition for the different states is similar to the XOR gate.

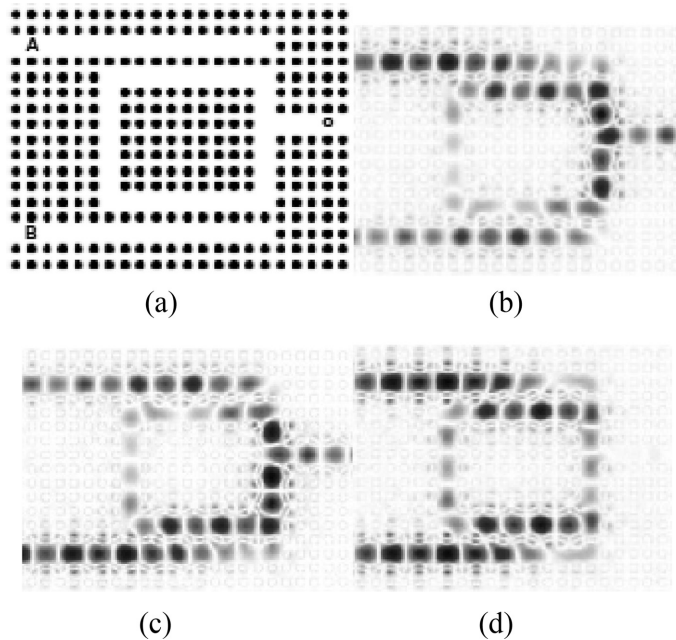
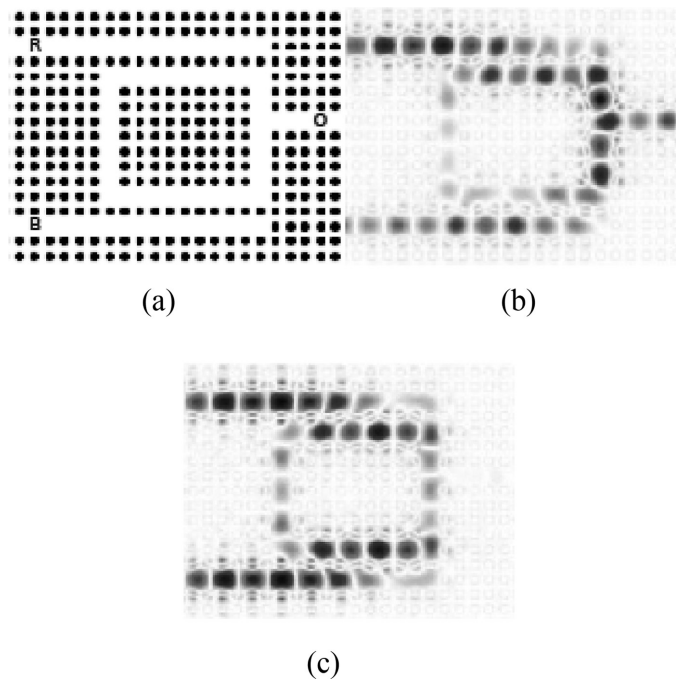


FIGURE 12.7

(a) The XOR gate design with the field profile analogous to the different XOR logic gate functions, (b) depicts “1 XOR 0 = 1,” (c) presents “0 XOR 1 = 1,” and (d) gives “1 XOR 1 = 0.”

**FIGURE 12.8**

(a) The NOT gate design with the field profile analogous to the different XOR logic gate functions, (b) depicts "0 NOT = 1", and (c) presents "1 NOT = 0".

The different OR logic operations with transmission is given in Table 12.1. Here the threshold determined as for the logic state 1 transmission output should be $>45\%$ and for logic state 0, it is $<5\%$.

Table 12.2 lists the different AND logic operations with corresponding transmission. Columns A and B present the inputs and O presents the output logic state. In this case, the chosen threshold conditions are as follows. If the transmission is $>90\%$, it termed as logic state 1 and for obtaining logic state 0, the transmission is $<50\%$.

Table 12.3 presents the different XOR logic operations. In this table, different logic functions with corresponding transmission at O are shown. To separate different logic states, some threshold conditions were used. The condition for the logic state to be 1, transmission should be $>45\%$ and for logic state 0, transmission is $<5\%$. When A and B are 1, the transmission is $<5\%$, and when either A or B is 1, it is $>45\%$. In the case of both A and B are 0, that is no signal applied to the inputs, so there is no transmission.

TABLE 12.1

The Logic Operations of Optical OR Gate

A (i/p)	B (i/p)	O (o/p)	Transmission (o/p) (%)
0	0	0	0
1	0	1	<60
0	1	1	<60
1	1	1	>60

TABLE 12.2

The Logic Operations of Optical AND Gate

A (i/p)	B (i/p)	O (o/p)	Transmission (o/p) (%)
0	0	0	0
1	0	0	<50
0	1	0	<50
1	1	1	>90

TABLE 12.3

The Logic Operations of Optical XOR Gate

A (i/p)	B (i/p)	O (o/p)	Transmission (o/p) (%)
0	0	0	0
1	0	1	>45
0	1	1	>45
1	1	0	<5

In [Table 12.4](#), NOT logic functions as well as respective transmission at output port O is given. The threshold conditions were similar to the case of above XOR logic gate. When the input A is 1, we have <5% transmission and when A is 0, the transmission is >45%.

The different gates OR, AND, XOR, NOT, and NOR can be operated with different wavelengths. These different operating wavelengths are calculated by measuring the transmittance and are listed in [Table 12.5](#). The corresponding CRs are also given to evaluate the performance of these gates. The CR is determined using the equation 1. The OR gate can be operated with five different wavelengths. In the case of OR logic gate as there is no signal applied to obtain 0 logic state, there will be no power output. So the CR cannot be calculated. The four different operating wavelengths and corresponding CRs of AND logic gate are given in the table. It has the same CR of 6 dB for all the wavelengths. The three

TABLE 12.4

The Logic Operations of Optical NOT Gate

R (reference)	B (i/p)	O (o/p)	Transmission (o/p) (%)
1	0	0	>45
1	1	0	<5

TABLE 12.5

The Operating Wavelengths and Corresponding Contrast Ratios for Different Optical Logic Gates

Logic Gate	Operating Wavelength (nm)	Contrast Ratio (dB)
OR	1524, 1551, 1572, 1642, 1659	
AND	1556, 1540, 1556, 1644	6:02, 6:02, 6:02, 6:02
XOR	1512, 1527, 1544	19:02, 20:04, 23:04
NOT	1512, 1527, 1544	19:02, 20:04, 23:04
NOR	1600, 1475, 1594	11, 6, 6

different wavelengths that can be used to perform XOR and NOT logic functions are given in the table with CRs. The CRs are different for different wavelengths and is about 23 dB for a particular wavelength. NOR gate can be operated with three wavelengths. The CR is slightly higher than AND gate for a particular wavelength.

12.6 Summary

This chapter has discussed the principles and operation of logic gates based on the two-dimensional rectangular photonic crystals. The gates considered were operating on the principle of interference, which has several advantages over other structures. The design of logic gates is a two-step process involving the band structure calculation and simulation of gates itself. A detailed discussion on the PWE method for the band structure calculation has been done. The working of various gates was studied using FDTD method, and the performances were represented using truth tables of the logic and field patterns obtained from FDTD simulation. This discussion will serve as an orientation toward the understanding and design of new logic devices based on photonic crystals.

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13

Designing Devices Using One-Dimensional Ternary Photonic Bandgap Material Structures

Anirudh Banerjee

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13.1 Introduction

One-dimensional (1D) photonic bandgap (PBG) structure has attracted considerable attention over the past two decades (Yablonovitch 1987; Yablonovitch 1993; Awasthi et al. 2006; Awasthi and Ojha 2008; Banerjee 2009a, 2009b; Banerjee 2010; Wu et al. 2010; Wang et al. 2014; Wu and Gao 2015). These 1D PBG structures are multilayer structures, which lead to the formation of PBGs or stopbands, in which propagation of electromagnetic waves at certain wavelengths is not allowed. With regard to the values of structural parameters, these 1D PBG structures have predetermined bands of wavelengths or frequencies that are reflected or transmitted by the structure, which are formed by generating periodic repetition of different material layers. However, these 1D PBG structures are classified into binary, ternary, and quaternary depending on the number of different material layers present in a period. The binary PBG structure consists of two different material layers in every period; the ternary PBG structure

consists of three different material layers in every period; the quaternary PBG structure consists of four different material layers in every period; and so on. The significant fact of 1D PBG structures is that the number of material layers in a period holds the key to performance of these structures. Recently, it was shown by several scientists, engineers, and researchers that the 1D ternary PBG structures demonstrate superior performances over 1D binary PBG structures in optical filtering (Awasthi and Ojha 2008), spectrum tuning (Banerjee 2010), omnidirectional reflection (Awasthi et al. 2006; Wang et al. 2014), bandgap extension (Wu et al. 2010), refractometric (Banerjee 2009a), and temperature sensing (Banerjee 2009b; Wu and Gao 2015). Thus, they are important for designing photonic devices. Hence, in this chapter, 1D ternary PBG structures are considered for the purpose of study. These structures are subjected to a change in number of periods, refractive indices of constituent materials, and angles of incidence of light on the structure and thicknesses of constituent material layers. The output spectra of these 1D ternary PBG structures, under these conditions, are computed using transfer matrix model (TMM). 1D ternary PBG structures based on Si/Bi₄Ge₃O₁₂/SiO₂ were taken for computations. Based on the observations, different ways are suggested and discussed in this chapter in order to design devices such as optical filters, reflectors, sensors, buffers, and multiplexers. This chapter also explores the idea of cascading more than one PBG structure to design wide-band reflectors, multiband, and narrow-band filters.

13.2 Theory

The 1D binary PBG structure consisting of alternate layers of refractive indices n_1 and n_2 with thicknesses d_1 and d_2 , respectively, is shown in Figure 13.1. Here, $d = d_1 + d_2$ is the period of the lattice. The binary structure shown in Figure 13.1 can be modified by sandwiching a thin layer of a third material of refractive index n_B and thickness d_B between the two layers of the binary structure periodically to form a ternary PBG structure as shown in Figure 13.2. Now this modified periodic structure, that is, the ternary structure, has alternate layers of refractive indices n_1 (first material layer), n_B (second material layer), and n_2 (third material layer), with thicknesses d_1 , d_B , and d_2 , respectively, in which $d = d_1 + d_B + d_2$ is the period of the lattice.

According to the optical transmission matrix theory (Banerjee 2009a, 2009b), for light incident from air on the multilayer at an angle θ_0 and for the s wave, the characteristic matrix $M[d]$ of one period is given by the following:

$$M[d] = \prod_{i=1}^l \begin{bmatrix} \cos \beta_i & \frac{-i \sin \beta_i}{p_i} \\ -ip_i \sin \beta_i & \cos \beta_i \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}, \quad (13.1)$$

where $l = 3$ (1, 2, and 3 signify the layers of refractive indices n_1 , n_B , and n_2 , respectively), $\beta_1 = \frac{2\pi n_1 d_1 \cos \theta_1}{\lambda_0}$, $\beta_2 = \frac{2\pi n_B d_B \cos \theta_2}{\lambda_0}$, and $\beta_3 = \frac{2\pi n_2 d_2 \cos \theta_3}{\lambda_0}$.

Here λ_0 is the free space wavelength, $p_1 = n_1 \cos \theta_1$, $p_2 = n_B \cos \theta_2$, and $p_3 = n_2 \cos \theta_3$, where θ_1 , θ_2 , and θ_3 are the ray angles inside the layers 1, 2, and 3, respectively, and are related to the angle of incidence θ_0 by

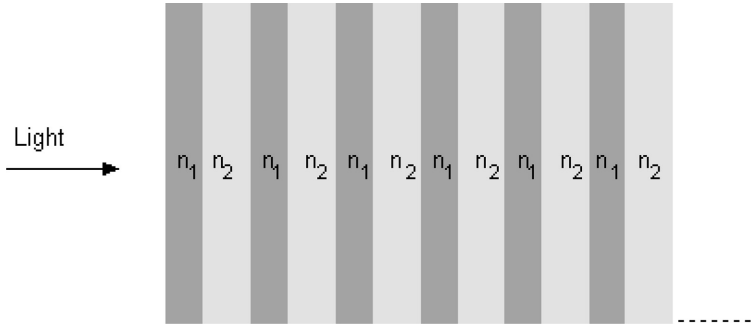


FIGURE 13.1
Schematic of 1D binary PBG structure.

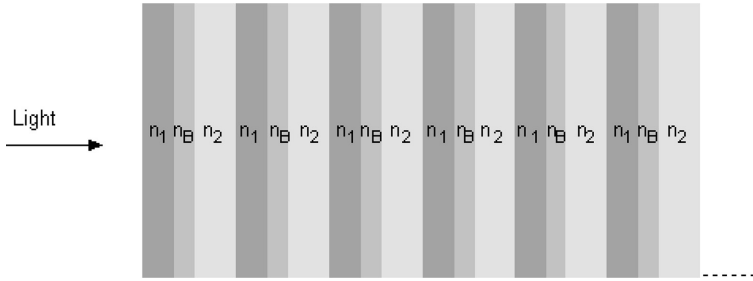


FIGURE 13.2
Schematic of 1D ternary PBG structure.

$$\cos \theta_1 = \left[1 - \frac{\sin^2 \theta_0}{n_1^2} \right]^{\frac{1}{2}}, \cos \theta_2 = \left[1 - \frac{\sin^2 \theta_0}{n_B^2} \right]^{\frac{1}{2}}, \text{ and } \cos \theta_3 = \left[1 - \frac{\sin^2 \theta_0}{n_2^2} \right]^{\frac{1}{2}}. \quad (13.2)$$

The matrix $M[d]$ in Equation (13.1) is unimodular as $|M[d]| = 1$.

For an N period structure, the characteristic matrix of the medium is given by the following:

$$[M(d)]^N = \begin{bmatrix} M_{11}U_{N-1}(a) - U_{N-2}(a) & M_{12}U_{N-1}(a) \\ M_{21}U_{N-1}(a) & M_{22}U_{N-1}(a) - U_{N-2}(a) \end{bmatrix} \equiv \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix},$$

where

$$M_{11} = \left(\cos \beta_1 \cos \beta_2 \cos \beta_3 - \frac{p_2 \sin \beta_1 \sin \beta_2 \cos \beta_3}{p_1} - \frac{p_3 \cos \beta_1 \sin \beta_2 \sin \beta_3}{p_2} - \frac{p_3 \sin \beta_1 \cos \beta_2 \sin \beta_3}{p_1} \right),$$

$$\begin{aligned}
M_{12} &= -i \left(\frac{\sin \beta_1 \cos \beta_2 \cos \beta_3}{p_1} + \frac{\cos \beta_1 \sin \beta_2 \cos \beta_3}{p_2} + \frac{\cos \beta_1 \cos \beta_2 \sin \beta_3}{p_3} \right. \\
&\quad \left. - \frac{p_2 \sin \beta_1 \sin \beta_2 \sin \beta_3}{p_1 p_3} \right), \\
M_{21} &= -i \left(p_1 \sin \beta_1 \cos \beta_2 \cos \beta_3 + p_2 \cos \beta_1 \sin \beta_2 \cos \beta_3 + p_3 \cos \beta_1 \cos \beta_2 \sin \beta_3 \right. \\
&\quad \left. - \frac{p_1 p_3 \sin \beta_1 \sin \beta_2 \sin \beta_3}{p_2} \right), \\
M_{22} &= \left(\cos \beta_1 \cos \beta_2 \cos \beta_3 - \frac{p_1 \sin \beta_1 \sin \beta_2 \cos \beta_3}{p_2} - \frac{p_2 \cos \beta_1 \sin \beta_2 \sin \beta_3}{p_3} \right. \\
&\quad \left. - \frac{p_1 \sin \beta_1 \cos \beta_2 \sin \beta_3}{p_3} \right).
\end{aligned}$$

U_N are the Chebyshev polynomials of the second kind, that is,

$$U_N(a) = \frac{\sin[(N+1)\cos^{-1}a]}{[1-a^2]^{\frac{1}{2}}}, \quad (13.3)$$

where

$$a = \frac{1}{2}[M_{11} + M_{22}]. \quad (13.4)$$

The transmission coefficient of the multilayer is given by the following:

$$t = \frac{2p_0}{(m_{11} + m_{12}p_0)p_0 + (m_{21} + m_{22}p_0)}, \quad (13.5)$$

and the transmissivity for this structure can be written in terms of transmission coefficient as follows:

$$T = |t|^2, \quad (13.6)$$

where

$$p_0 = n_0 \cos \theta_0 = \cos \theta_0 \text{ as } (n_0 = 1).$$

The transmissivity of the structure for p wave can be obtained using expressions (13.1)–(13.6) with the following values of p :

$$p_1 = \frac{\cos \theta_1}{n_1}, \quad p_2 = \frac{\cos \theta_2}{n_B}, \quad p_3 = \frac{\cos \theta_3}{n_2}, \quad \text{and } p_0 = \cos \theta_0.$$

13.3 Results, Discussion, and Device Design

13.3.1 Effect of Number of Periods “ N ” on Transmittance and Its Use in Designing Reflectors, Filters, and Buffers

For numerical computation, a 1D ternary PBG material structure is taken. The first material layers are of Si ($n_1 = 3.3$), the second material layers are of $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ ($n_B = 2.05$), and the third material layers are of SiO_2 ($n_2 = 1.46$), where d_1 , d_B , and d_2 are 105, 10, and 190 nm, respectively. Using TMM described in Section 13.2, the transmission spectra have been calculated for normal incidence of light on the structure. Figure 13.3a–c shows plots of transmittance versus wavelength for $N = 3, 6$, and 9, respectively. Comparisons of these figures show that reflectance of the stopband increases with increase in the number of periods. Thus, for designing reflectors, the number of periods in the structure can be kept high to obtain sufficient reflectance in the stopband region. A filter or a reflector with high stopband reflectance can be fabricated by choosing high values of N .

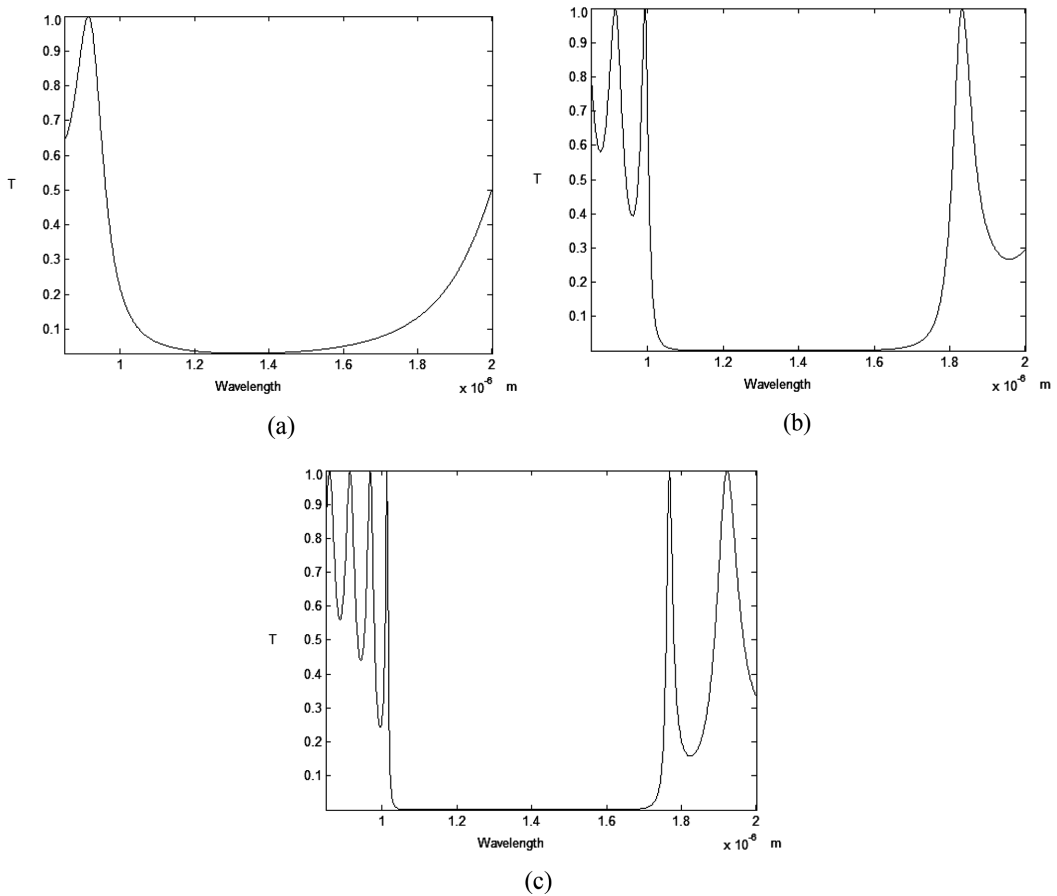


FIGURE 13.3

Transmission spectra of $\text{Si}/\text{Bi}_4\text{Ge}_3\text{O}_{12}/\text{SiO}_2$ structures with (a) $N = 3$, (b) $N = 6$, and (c) $N = 9$.

Besides increasing reflectance of stopband region, the high value of N will also increase the optical path length of light in the structure; hence optical buffers with long delay times can be fabricated using these structures.

13.3.2 Effect of Refractive Index Changes and Its Use in Reflectors, Refractometric Sensors, Electrical Tuning, Buffering, and Multiplexing

Figures 13.4–13.6 show the transmission spectra for the above-mentioned 1D ternary PBG structure with change in refractive index of first, second, and third material layers, that is, with $n_1 = 3.3, 3.4$, and 3.4 ; $n_B = 2.05, 2.15$, and 2.25 ; and $n_2 = 1.46, 1.56$, and 1.66 , respectively. Light is incident on these structures normally. Comparison of these figures show that the wavelength range of reflection increases with increasing refractive index. The spectrum also shifts toward higher wavelengths. Therefore, due to wide stopbands, photonic crystals with high refractive index are especially useful as reflectors. The high refractive index in the periodic structures plays a vital role for the PBGs to occur or to become more pronounced for a given structure. There are two reasons for the importance of high refractive index. First, each photonic crystal structure has a threshold value of refractive index contrast to exhibit a PBG, which is attributed to the fact that interfaces of two dielectrics with higher contrast of refractive indices tend to scatter waves from any direction, so stopbands to any direction, a PBG, are more likely to take place.

Second, the higher the refractive index contrast is, the fewer layers are necessary to have sufficient PBG effects. Each layer of the photonic crystal partially reflects the propagating wave. Consequently, if each layer reflects more waves due to a higher refractive index contrast, sufficient net reflections can be achieved by fewer layers than a structure with the same configuration but with a lower refractive index of constituent material layers. The spectrum shift due to refractive index change allows these structures to be used as refractometric optical sensing elements, where a change in the refractive index can be sensed by detecting a shift in the transmission spectrum. Properly designed PBG structures with empty layers can

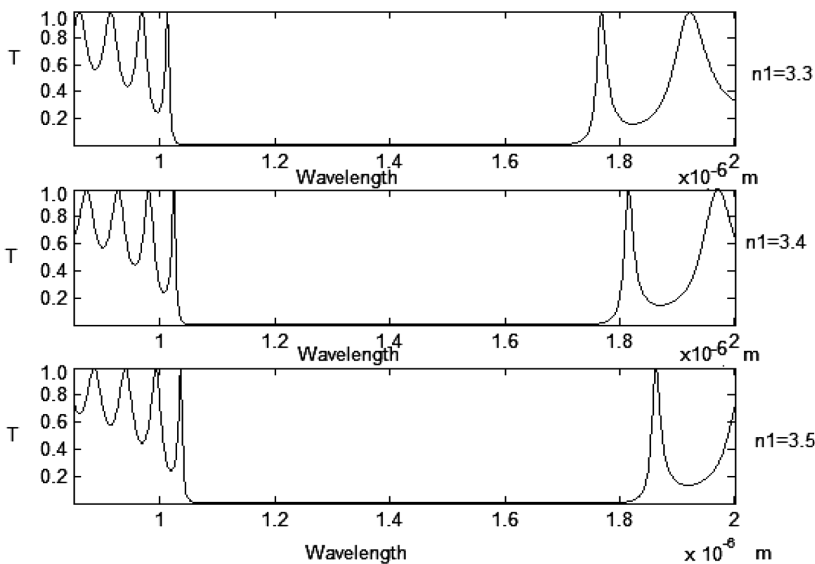


FIGURE 13.4
Effect of increasing refractive index of first material layers.

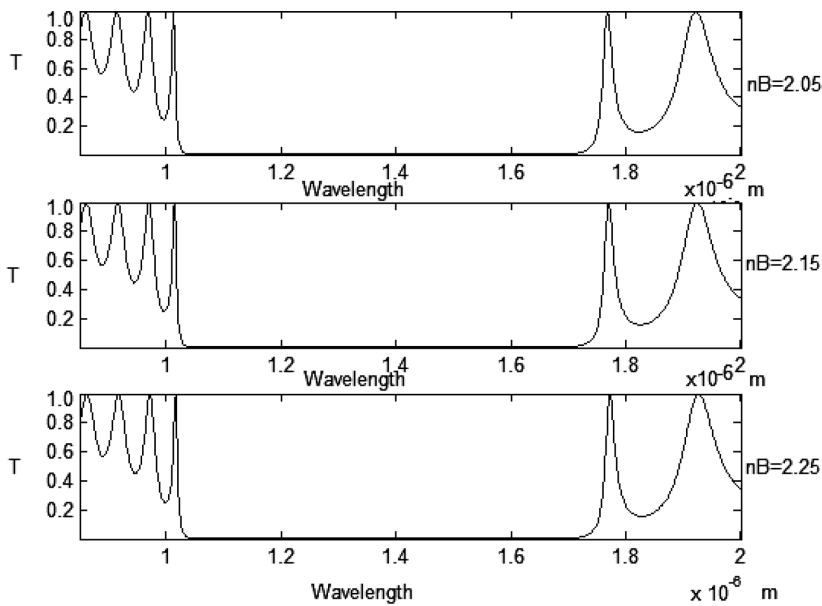


FIGURE 13.5
Effect of increasing refractive index of second material layers.

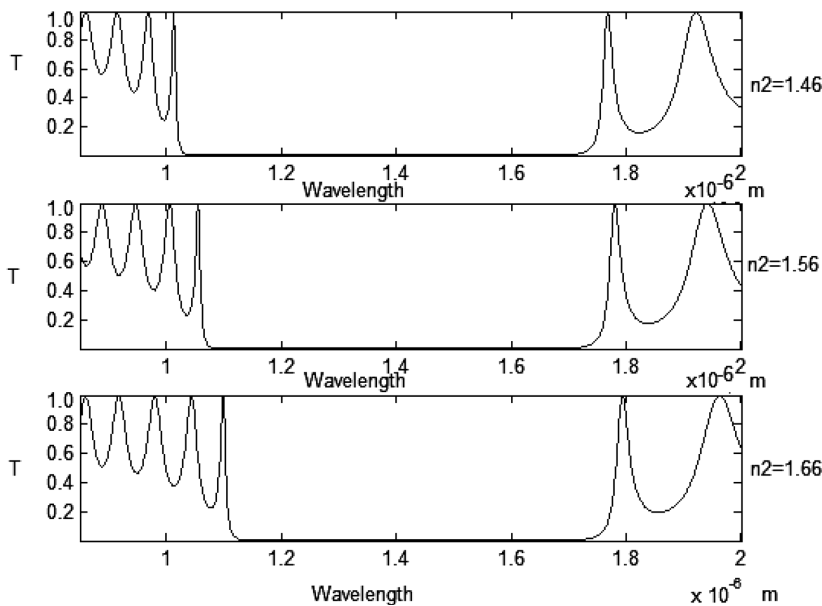


FIGURE 13.6
Effect of increasing refractive index of third material layers.

be used as adulteration sensors. The empty layers can be first filled with original fluid and then by adulterated fluid. The adulteration can be very easily detected by comparing the spectra of structures with original and adulterated fluids. Not only the adulteration can be detected, but the amount of adulteration can also be estimated by measuring the spectrum shift. Further, electro-optic materials can be embedded in the structure and electric field can

be applied using electrodes. Due to linear electro-optic effect or Pockels effect, the refractive index of material changes in proportion to the applied electric field. This causes the transmission spectrum shift, hence making it possible to electrically tune the transmission spectrum of this 1D PBG structure. Thus, electrically tunable optical filters and reflectors can be fabricated.

Using electro-optic effect, not only the transmission and the reflection spectra can be tuned, but also the data transmission time or delay time through the PBG structure can also be tuned. As the refractive index change will also change the optical path length of light, thus, electrically tunable optical buffers and time division multiplexers can also be fabricated using these structures. The idea of electrical tunability can be implemented without investing too much of energy, as the consumption of electrical energy in electro-optic effect-based devices is extremely small (Barrios et al. 2003; Miller 2012). Further, the electro-optic effect-based tuning is faster than thermal or chemical tuning used in PBG structures. So, high-speed tuning can be achieved in electrically tunable optical filters and reflectors. Besides this, the application of electric field can be very easily controlled by a remote computer. The electrical tunability of a PBG structure provides an additional advantage of computer controllability, which makes it possible to use this structure in high-speed digital networks and systems. The electro-optic effect-based transmission spectrum shift can also be utilized to nullify the transmission spectrum shift due to temperature change. Therefore, the electro-optic effect-based compensation circuits can be used to stabilize the performance of the PBG structures in temperature-unstable environments. The knowledge of effects of number of periods in the structure and the electro-optic tuning can be used to fabricate PBG structures with long and tunable delay times.

13.3.3 Effect of Thickness Change and Its Use in Designing Filters, Reflectors, Pressure, and Temperature Sensors

Normal incidence of light was assumed while using the 1D ternary PBG structure discussed in previous sections, and the transmission spectra were calculated for different values of d_1 , d_b , and d_2 as shown in [Figures 13.7 to 13.9](#). It was found that by changing the thickness, the transmission and reflections bands and their widths can be changed. Thus, these structures can be used as stress, pressure sensors, and temperature sensors, as any stress or pressure on the structure will change the thickness of the material layers. Particularly, a rise in temperature will change the refractive index and thickness of the material layers, which will shift the output spectrum. This idea can be utilized to design thermally tunable optical filters and reflectors, where transmission and reflection band wavelengths can be tuned by changing the ambient temperature. Therefore, not only stress, pressure, and temperature tunable filters and reflectors, but sensors based on these parameters can also be designed. In temperature sensors, the temperature changes can be detected by monitoring the transmission spectrum of the structure. The exact temperature can also be determined by calculating the shift in output spectrum. In pressure or stress measurement systems, the stress or pressure-induced thickness change can be measured by calculating the spectrum shift.

13.3.4 Effect of Angle of Incidence Change and Its Use in Designing Optical Filters, Reflectors, and Sensors

The effect of angle of incidence of light on $\text{Si}/\text{Bi}_4\text{Ge}_3\text{O}_{12}/\text{SiO}_2$ structure has been then investigated. [Figures 13.10 through 13.13](#) show the transmission spectra of $\text{Si}/\text{Bi}_4\text{Ge}_3\text{O}_{12}/\text{SiO}_2$ structure at angles of incidences 0° , 30° , 45° , and 60° , respectively. Dotted curves are of p polarization and solid curves are of s polarization.

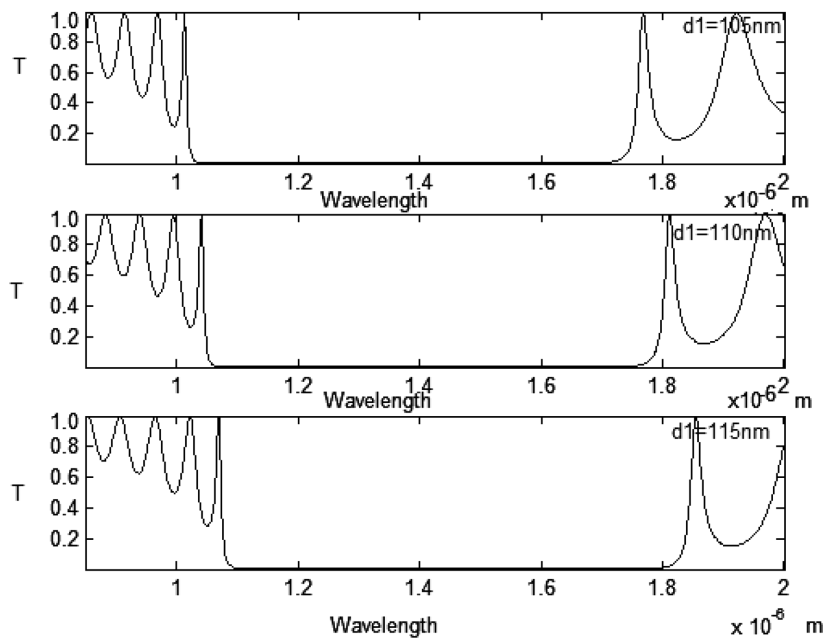


FIGURE 13.7
Effect of increasing thickness of first material layers.

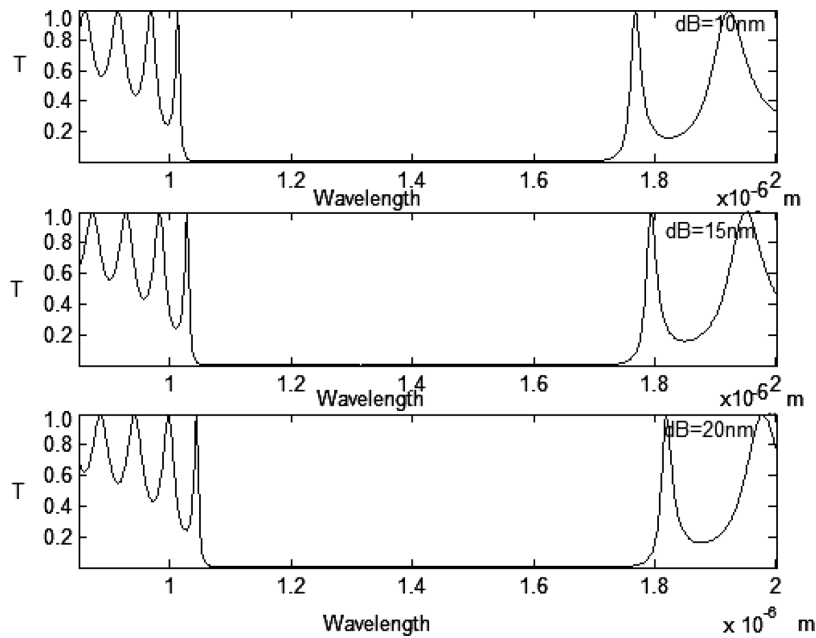


FIGURE 13.8
Effect of increasing thickness of second material layers.

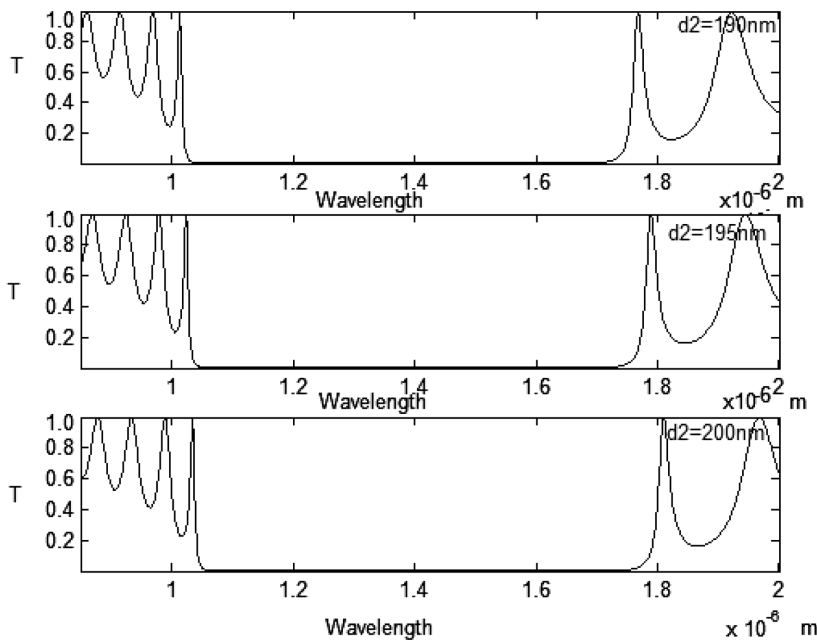


FIGURE 13.9
Effect of increasing thickness of third material layers.

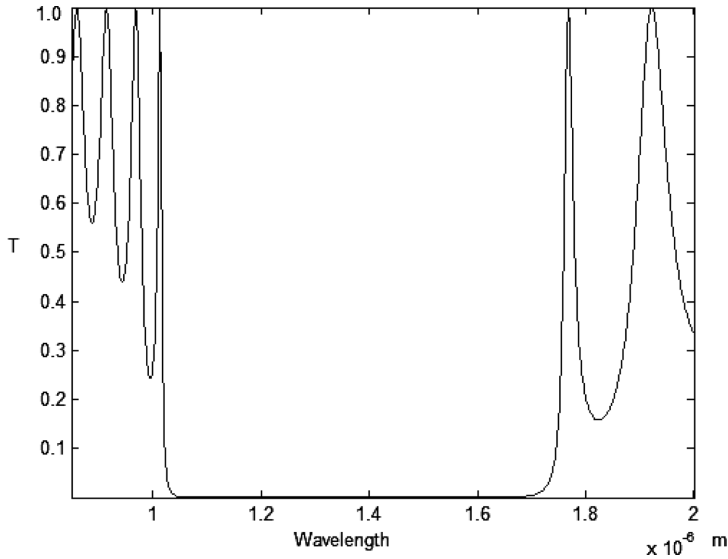
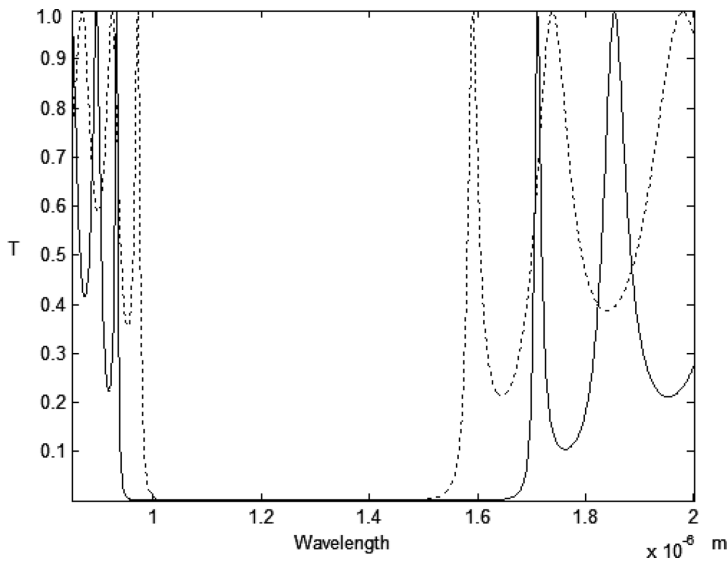
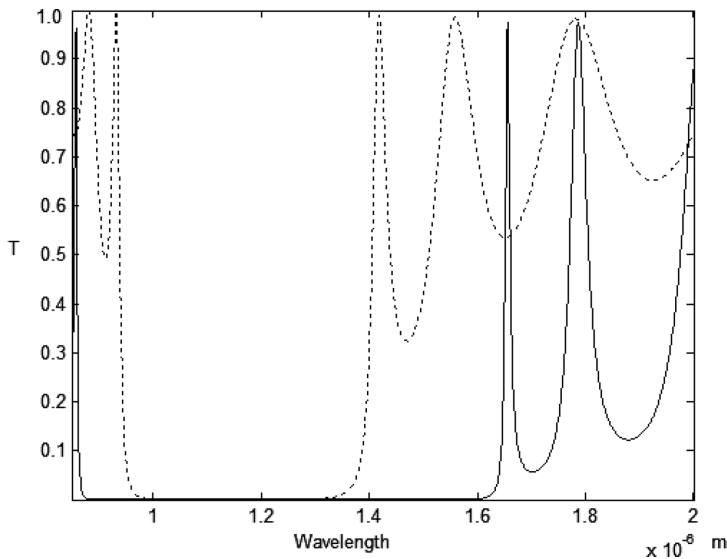


FIGURE 13.10
Transmission spectrum of the structure at normal incidence of light.

From [Figures 13.10](#) through [13.13](#), it is found that a wide region of allowed wavelengths is obtained for normal incidence of light on the structure, but on increasing the incidence angle, the allowed range becomes narrower and narrower while shifted toward the lower wavelength side. These allowed bands give the different ranges of wavelengths that can be transmitted through the structure. As the ranges of transmission and bandwidth depend

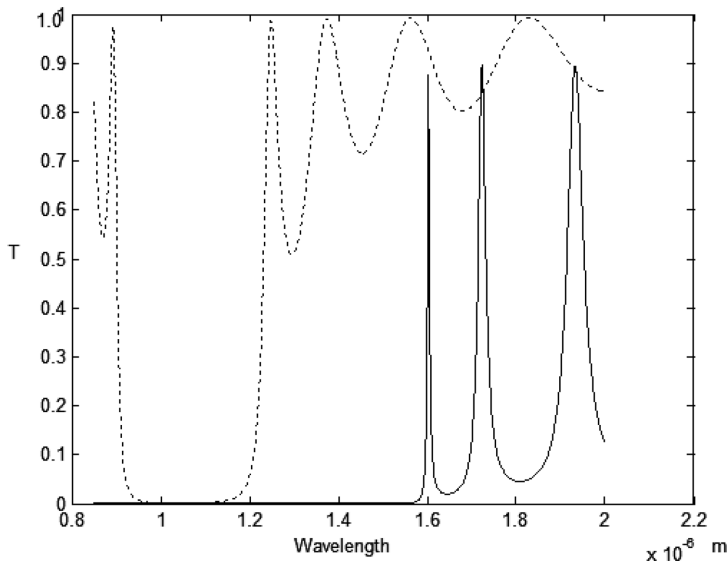
**FIGURE 13.11**

Transmission spectrum of the structure at an angle of incidence 30° .

**FIGURE 13.12**

Transmission spectrum of the structure at an angle of incidence 45° .

on the values of control parameter N , refractive index of layers, thickness of layers, and angle of incidence, therefore, it is possible to obtain the desired ranges of the electromagnetic spectrum transmitted or reflected through the structure by changing the values of these parameters and/or by varying the angle of incidence. If we fix the values of other parameters, then by varying the angle of incidence of light, we can get different wavelengths filtered or reflected through the structure. The same structure can transmit and reflect different wavelengths of light without changing the structural parameters.

**FIGURE 13.13**

Transmission spectrum of the structure at an angle of incidence 60° .

Thus, tunable optical filters or reflectors can be designed using these structures. The idea of shifting transmission and reflection spectrum by changing the angle of incidence of light can also be used to design stress, strain, and pressure sensors. In these sensors, an optical fiber may be aligned in such a way that it projects light at a certain angle to the PBG structure. Here the optical fiber may be used as a stress, strain, and pressure-sensing element. Due to applied stress or strain or pressure, the alignment of optical fiber will change; hence the light projection angle to the PBG structure will be changed to generate the output spectrum shift, which can be measured by calculating this shift in the output spectrum. Combining spectrum tuning with electrical and/or thermal tuning, the tunable transmission and reflection range of wavelengths can be drastically extended. Thus, the same structure can be used for several ranges of wavelengths, which eliminates the cost and efforts to be required to fabricate different 1D PBG structures for transmitting and reflecting different sets of wavelengths.

13.3.5 Effect of Cascading Structures and Its Use in Designing Filters and Reflectors

The 1D PBG structures with different output spectra can be cascaded in a series to design wide-band reflectors, multiband, and narrow-band filters. The cascading of structures allows the use of already fabricated 1D PBG structures to design multiband filters and wide-band reflectors. This eliminates efforts and cost of fabricating new structures to be used as narrow-band, multiband filters, and broadband reflectors. The ideas of cascading of 1D PBG structures are shown in Figures 13.14 through 13.16. In Figure 13.14, two PBG structures are cascaded. Figure 13.15 shows cascading of two tunable PBG structures. Figure 13.16 shows the idea of cascading of more than two PBG structures. As shown in Figure 13.14, the light is made incident on the input side of PBG structure 1. The light transmitted through the PBG structure 1 comes out from the output side of structure 1, which depends on its structural parameters. This light can then be projected on the PBG structure 2. The light output from the PBG structure 1 acts as an input to the PBG structure 2,

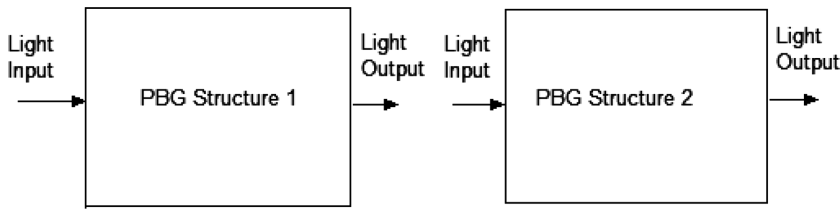


FIGURE 13.14
Cascading of two 1D PBG structures.

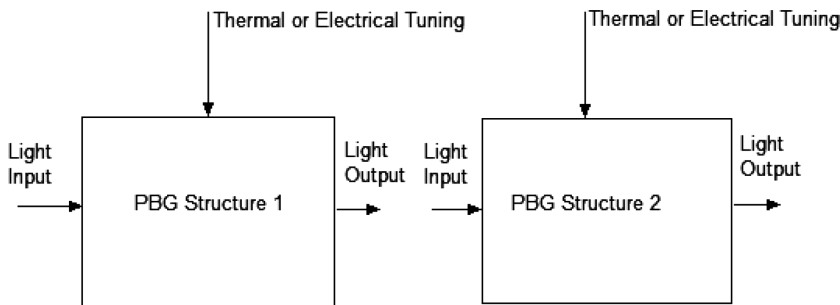


FIGURE 13.15
Cascading of two tunable 1D PBG structures.

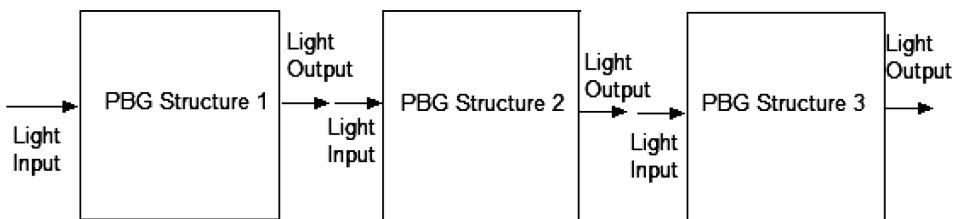


FIGURE 13.16
Cascading of three 1D PBG structures.

which transmits or reflects wavelengths based on its structural parameters. The light coming out from output side of PBG structure 2 will constitute the output spectrum for this cascaded structure. Two or more than two PBG structures can be cascaded to manipulate transmission and reflection spectrum per the requirement. PBG structures with different reflection bands can be cascaded to produce a cascaded system with wide reflection band. PBG structure 1 with reflection band from “a” nm wavelength to “b” nm wavelength can be cascaded with PBG structure 2 with reflection band from “b” nm wavelength to “c” nm wavelength to produce a reflection band from “a” to “c” nm. Similarly, more structures can be cascaded to produce wide reflection bands. Thus, several narrow-band reflectors can be cascaded to produce a wide-band reflector. A PBG structure with transmission band from “a” nm wavelength to “b” nm wavelengths can be cascaded with a PBG structure 2 with reflection band from “a + 1” nm wavelength to “b” nm wavelength to produce a narrow-band filter with narrow transmission band around “a” nm wavelength. A PBG structure with transmission band from “a” nm wavelength to “b” nm wavelengths can be cascaded with a PBG structure 2 with reflection band from “a + 1” nm wavelength to “b – 1” nm

wavelength to produce two narrow transmission bands around “a” and “b” nm wavelengths. Thus, multiband filters can also be designed by cascading 1D PBG structures. The transmission bandwidths in multiband filters can be controlled by choosing the gaps between photonic band edges in the cascaded structures. By shifting bands in one of the cascaded structures either electrically or thermally, bandwidths of the transmission bands or reflection bands can also be tuned in a desired manner.

13.4 Conclusion

In this chapter of the study of effects of number of periods, refractive indices of material layers, thickness of material layers, and angle of incidence of light on Si/Bi₄Ge₃O₁₂/SiO₂-based 1D ternary PBG material structure has been performed. The effect of cascading of these 1D PBG structures has also been discussed. An increase in N increases reflection, while increase in refractive index and angle of incidence increases reflection and the width of reflection band, that is, transmission bands get narrower. The high value of N is especially useful in designing broadband reflectors and optical buffers with long delay times. The output spectrum of the structure can be tuned by changing the refractive indices of constituent material layers in the structure, which helps in designing tunable filters, reflectors, buffers, and multiplexers. The use of electro-optic material layers in the 1D PBG structure opens up the possibility of electrical tuning of transmission and reflection bands in the structure, which also enables to tune the data transmission time through the structure electrically. Using an empty layer in the structure, we can use 1D PBG structures in detecting adulteration in fluids. The effect of thickness of material layers is also dominant in determining the transmission or reflection bandwidth. Based on the idea, stress, pressure and temperature sensors, thermally tunable filters, and reflectors can be designed. By changing the angle of incidence of light on the structure, the transmission and reflection bands through the structure can also be tuned, which helps in designing stress, strain, and pressure sensors. By cascading 1D PBG structures, broadband reflectors, multiband, and narrow-band optical filters can also be designed. The idea of cascading of PBG structures allows the use of same PBG structures for broadbanding of reflection bands, multi, and narrow banding of transmission bands without needing to fabricate new 1D PBG structures for the above-mentioned purposes.

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14

Interference-Based All-Optical Photonic Crystal Logic Gates

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14.1 Introduction

All-optical denotes that there is no need of optical-electrical-optical (O-E-O) conversion. From the past decades, researchers have been showing more attention on all-optical signal processing schemes for their application in high-speed optical networks and optical computing. They can increase their operational speed to Tbps and reduce the power consumption to a greater extent unlike the conventional O-E-O signal processing schemes (Zeng et al. 2010). Recently, many researchers have been focusing much on all-optical logic gates for their applications in real-time optical processing and information communications (Barrios 2004; Dumeige et al. 2006; Igarashi and Kikuchi 2008), because all-optical signal processing can deal with large bandwidth signals and large information flow and have no need of O-E-O conversion (Rani et al. 2013). These gates have particular significance

in various optical networking functions (Ramous et al. 2005; Tang et al. 2014) such as addressing, optical computing, clock recovery, header recognition, and signal regeneration. In order to design these all-optical logic gates, several approaches have been followed in the literature so far, such as semiconductor optical amplifier (SOA) (Soto et al. 2002), SOA-based Mach–Zehnder interferometer (MZI) (Kim et al. 2006), optical nonlinearity (Fujisawa and Koshihara 2006; Yabu et al. 2002), periodically poled lithium niobate (PPLN) (Wang et al. 2008), fiber Bragg grating (FBG) (Lee et al. 2006), and photonic crystal (PC) fiber (Uthayakumar et al. 2013). SOA-based designs usually have low-operation speed due to large response time, and also they experience unavoidable spontaneous emission of noise. Logic gates with optical nonlinearity are limited by high power consumption and narrow operating frequency range. PPLN waveguide-based logic gates have been reported with advantages such as ultrafast response, complete transparency, negligible spontaneous emission of noise, and multifunctionality but have temperature and polarization dependencies and minimum size limitations. The devices with FBGs have shown much difficulty in providing very closed channel spacing and become a critical problem in achieving high degree of integration. The approaches presented above are different from each other in terms of complexity, precision, reliability, ease of integration, and finally the performance speed. To overcome these limitations, researchers have been concentrating on the optical materials such as PC (Christina and Kabilan 2012; Liu et al. 2013; Wu et al. 2012; Younis et al. 2014) and liquid crystal (Khan and Nejib 1987). PC-based logic gates act as a replacement to these structures as they are compact in size, have reduced power consumption, and high speed with dimensions of a few wavelengths of light being confined (Johnson and Joannopoulos 2003).

PC is a low-loss periodic dielectric medium that can guide, control, and manipulate the optical signal (Joannopoulos et al. 1995). It was originally introduced to control spontaneous emission of atoms (Bykov 1972). It is the periodic structure of PC that obstructs the passage of certain range of electromagnetic frequencies, called photonic bandgap (PBG), thereby preventing the spontaneous emission (Bykov 1972, 1975). As these structures provide a forbidden frequency band for the light signals, the devices created on the PCs are also called as PBG devices (Joannopoulos et al. 1995). Periodic interactions in the PC structures create the PBGs, and the frequencies that come under these bands cannot propagate inside these structures. Thus, in many aspects, the behavior of light in periodic dielectrics is similar to the behavior of electrons in the periodic potential of a solid-state crystal (Yablonovitch 1993), which means that manipulation of the flow of light in the PC is similar to the manipulation of flow of electrons in the solid-state circuits. Hence, the periodic structures are used for the strong localization of light in a disordered dielectric lattice (John 1987).

PC is used to construct all-optical devices with dimensions of few wavelengths of light being confined. This is a structure wherein the dielectric constant changes periodically in a particular direction, and so there are one-, two-, and three-dimensional PCs. PC devices can limit, control, and guide the light in the nanometer scale due to bandgap engineering. Normal photonic devices cannot limit the desired optical mode in nanometer scale due to high loss in refraction and total internal reflection (TIR) (David and Lorenzo 2011; Sibilia et al. 2008). Also the researchers paying much attention toward these type of structures show that there is a possibility of fabricating them using abundantly available Si material.

Inside a uniform PC, as it was discussed earlier, the signals cannot propagate with frequencies in PBG range. By inserting defect/defects, the light mode can be limited and even localized in the PC lattice. Three types of defects that can be inserted into the PC are point defect, line defect, and surface defect, which help PC to act upon the application for which it is designed. This flexibility provides the PC structure to have a strong ability to confine

and guide the light and to limit the modes. Further, this flexibility of making defects plays a main role in designing optical elements.

The study of PC holds much dynamic interest in many novel applications due to its unique features and advantages. Since the researchers have been proposing from the past decades, many optical devices such as modulators (Nguyen et al. 2012), waveguides (Fasihi and Mohammadnejad 2009), power splitters (Gaffari et al. 2008), filters (Djavid et al. 2008), lasers (Sevin et al. 2010), multiplexers and demultiplexers (Rawal and Sinha 2009), wave-length converters (Khorshidahmad and Kirk 2010), polarization converters (Tanaka et al. 2010), triplexers (Shi et al. 2006), and encoders (Lee et al. 2010) use PCs with successful results.

As the PC provides many applications as part and parcel of the optical systems, attempts have also been undergoing toward the design and development of optical computing systems. Many literatures show that several attempts have been made to design the logic gates with successful performance, which are the basic components in the development of optical computing systems. Apart from the logic gates, many other combinational and sequential logic systems have also been proposed (Iman and Rafah 2016; Liu et al. 2008; Moniem 2015). In this chapter, a simple technique has been presented using which one can define a simple T-shaped waveguide as a high-contrast logic gate, and examples have been given on the design of single-stage and double-stage structures with the effect on the output performance. The remaining part of this chapter is constituted as follows. [Section 14.2](#) introduces various phenomena used in the literature for the design of PC-based logic gates. [Section 14.3](#) describes the analysis on the L-bend and T-shaped waveguides using coupled mode theory (CMT). [Section 14.4](#) explains the usage of T-shaped waveguide mapped on a PC as a logic gate, which is followed by the description on connecting these gates in single-stage and double-stage structures in [Section 14.5](#). [Section 14.6](#) concludes with discussion on the methodology presented in the chapter to describe the logic gates.

14.2 Introduction to “PC”-Based Logic Gates

Optical material plays an important role in control and manipulation of the light, which can be done using semiconductors in the periodic structures such as PCs (Yablonovitch 1993). The main aim of inventing the PC is to create the structures that can allow light in smaller space for a longer duration (Sibilia et al. 2008), but they would allow the light to be guided or controlled for some wavelengths. The propagation of waves in a source-free, nonmagnetic dielectric isotropic medium is governed by Maxwell’s equations. By assuming linear, isotropic, and transparent medium, the behavior of the mixed dielectric medium is formulated using Maxwell’s equations. As the Maxwell’s equations are assumed to be linear, the time dependency is separated out by expanding the E and H fields into harmonic modes (Joannopoulos et al. 1995). For a dielectric material, the material properties can also be characterized using refractive index n as n is equal to $\sqrt{\epsilon_r}$. After formulating the behavior of the dielectric medium using Maxwell’s equations, the eigenvalue equation for the magnetic fields can be found (Joannopoulos et al. 1995) as follows:

$$\nabla \times \left(\frac{1}{\epsilon(r)} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r) \quad (14.1)$$

This is the principal equation that describes the propagation properties of electromagnetic waves in PC. The electric field can also be obtained from the above equation. For a harmonic mode in mixed dielectric medium, the above differential equation of $H(r)$ becomes the central part of the Maxwell's equation. It performs various operations on $H(r)$, and if the function $H(r)$ is really an electromagnetic mode, the result will be constant times of it. If the resultant of an operation of a function is the function itself with multiplicative constant, then that function is called as eigenfunction or eigenvector, and the multiplicative constant is referred to be eigenvalue. The eigenvectors are the field patterns of harmonic modes, whereas the eigenvalues are proportional to the squared frequencies of those harmonic modes (Joannopoulos et al. 1995). As shown in the above equation, $H(r)$ and $(\omega/c)^2$ are basically the eigenvectors and eigenvalues, respectively.

From the past decades, researchers have been working on PC structures in designing the optical logic gates because of their advantages such as low power consumption, high switching speed, and also ease of integration, which make it possible to create optical integrated circuits using them. This section provides information about the classification of PC-based all-optical logic gates according to the literature available. These are categorized into three types based on the principle of operation involved, which includes resonance, self-collimation, and interference. Each class is further subclassified based on the type of the structure and the material used. An overview about these classifications is shown in Figure 14.1.

In resonance-based logic gates, the basic unit is a ring resonator with waveguides that operate at resonant condition. In the basic unit, a ring resonator is placed in between top and bottom waveguides, or sometimes a T-shaped structure is formed with one of the waveguides that are placed adjacent to the ring resonator. Between the two waveguides, one is called as a bus waveguide through which an electromagnetic wave is sent and the other one is called as a drop waveguide into which the same wave is dropped at the

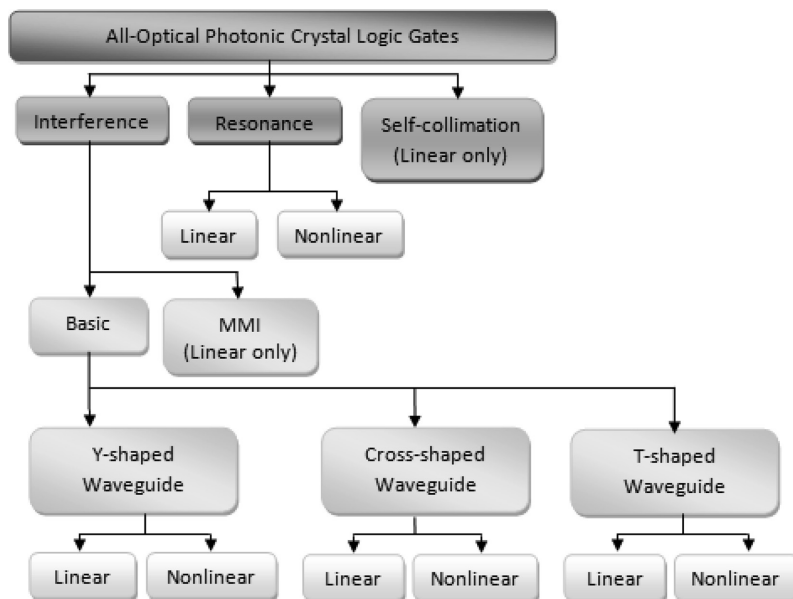


FIGURE 14.1
Classification of photonic crystal-based all-optical logic gates.

resonant condition. At resonance frequency or wavelength, an electromagnetic wave from the bus waveguide couples with the ring resonator and drops it into the drop waveguide. Both optical linearity and nonlinearity have been used in these designs (Andalib and Granpayeh 2009; Bao et al. 2014).

Self-collimation is a phenomenon by which an incident light can propagate without diffraction and engineering defects in a PC, which has led many researchers to pay attention toward it (Christina and Kabilan 2012). This phenomenon allows the light of a diverge input beam to be emitted and collimated without nonlinearity (Kosaka et al. 1999). Self-collimation need not require lateral confinement compared with the engineered defects-based PC to prevent either the beam divergence or diffraction broadening (Majid et al. 2012). Moreover, self-collimation is independent of light intensity, frequency range, and nonlinearity (Majid et al. 2012).

In interference-based method, the logical function of the gate depends on the interference of the applied input lights. The type of interference likely to happen is related to the phase and/or the path difference between the input lights (Zhu et al. 2006), and both linear and nonlinear materials are used to design these logic gates. The length and width of the waveguide provided for interference also matter the type of the interference, which in turn specifies the type of logical function. The logic gates designed under this method are further classified with respect to the type of structure or waveguide used.

There are three phenomena mostly been used in the design of PC-based logic gates. Some of the designs include both resonance and interference concept to boost up the performance (Aryan et al. 2015). In order to evaluate the performance of PC-based logic gates, the following parameters are used as metrics, and they are as follows:

1. Power consumption
2. ON to OFF contrast ratio
3. Bit rate
4. Response time.

Basically, power consumption of a PC structure depends on the type of the material used. Power consumption is low for the structure with linear materials (Esmaeili and Cherri 2014). ON to OFF contrast ratio or the extension ratio is the parameter using which one can measure the discrimination between the power levels of *logic "0"* and *logic "1"*. For better performance, the PC-based logic gates should provide the contrast ratio that is as high as possible. For all the PC-based logic gates, the ON to OFF contrast ratio or the extinction ratio is measured using the expression (Christina and Kabilan 2012; Liu et al. 2013; Wu et al. 2012; Younis et al. 2014):

$$CR = 10 \log \frac{P_1}{P_0}, \quad (14.2)$$

where P_1 is the output power of *logic "1"* and P_0 is the output power of *logic "0"*, and the units are in decibels. Normally, the minimum (maximum) value of contrast ratio is obtained by taking the lower (higher) value of the output power of *logic "1"* and the higher (lower) value of the output power of *logic "0"*. Bit rate or the operating speed is the reciprocal of the response time, which is the sum of the rising time (t_r) and the recovery time or the falling time (t_f) (Liu et al. 2008).

14.3 L-Bend, Straight, and T-Shaped Waveguides

Among the above-mentioned three phenomena, interference-based logic gate designs have achieved superior performance in terms of contrast ratio and response time. These logic gate designs have achieved the contrast ratio of more than 40 dB (Shaik and Rangaswamy 2017a) with a response time of less than 0.4 ps and less complexity. In these logic gates, structures are designed with Y-shaped (Rani et al. 2013) and cross-shaped waveguides (Wu et al. 2012) and also with the waveguides depend on multimode interference (Tang et al. 2014). Among these designs, the structures with MMI provide higher contrast ratio of above 40 dB with simple and compact size. From the literature, it has been observed that the ratio and the response time can still be improved using simple T-shaped waveguide and allowing the input light signals to interfere constructively or destructively with respect to the phase difference (Shaik and Rangaswamy 2017b, 2018). In this chapter, the way of using interference concept in T-shaped waveguide for the realization of logic gates is explained. The applicability of the T-shaped waveguide for logic gate functions is analyzed using CMT. The analysis is started with L-bend waveguide followed by its conversion into T-shaped waveguide.

14.3.1 L-Bend Waveguide

According to CMT, the waveguide branches are assumed to be connected to a resonator, which means the branching region is considered to be a resonator or a cavity (Haus 1984). The CMT depends on the differential equation that describes the balancing between the incoming and outgoing fields. Inside the lossless cavity, the resonant mode oscillates with frequency ω_o and consists of an amplitude a , which is normalized such that $W = |a|^2$, where the term W indicates that the energy is stored inside the cavity. Because of the intrinsic losses and the losses due to coupling with the waveguide branches, the cavity may lose its energy. The decay rates in the mode amplitude a due to these intrinsic and coupling losses are indicated as $1/\tau_o$ and $1/\tau_i$, respectively, where $i = 1, 2, 3, \dots$, which refers to the waveguide branches.

Using CMT, the transmission and reflection properties of the model can be ascertained, which relates the resonant mode amplitude a to the amplitudes of incoming and outgoing waves represented by S_{+i} and S_{-i} , respectively. The incident wave with amplitude S_{+i} couples with the cavity by coupling coefficient κ_i , and the power carried by the incident wave is given by $|S_{+i}|^2$ (Haus 1984). The model focuses on single-mode cavity with intrinsic and coupling losses, and the theoretical model for L-bend waveguide is shown in Figure 14.2. From the theoretical model, the derivative of the mode amplitude is given by the following:

$$\frac{da}{dt} = j\omega_o a - \left(\frac{1}{\tau_o} + \sum_{i=1}^3 \frac{1}{\tau_i}\right)a + \sum_{i=1}^3 \kappa_i S_{+i}, \quad (14.3)$$

$$\text{where } \kappa_i = \sqrt{\frac{2}{\tau_i}}$$

The theoretical model of the L-bend waveguide is considered to have symmetrical waveguide branches and lossless resonator to determine the output transmission at resonance (Manolatou et al. 1999). At this condition, the output performance is same when the ports are excited individually. Here, only port 1 is assumed to be excited with S_{+1} at a time dependence of $e^{j\omega t}$, and thus the incoming wave at port 2 is considered to be zero as it is not being excited. From this, the mode amplitude of the resonator can be given as follows:

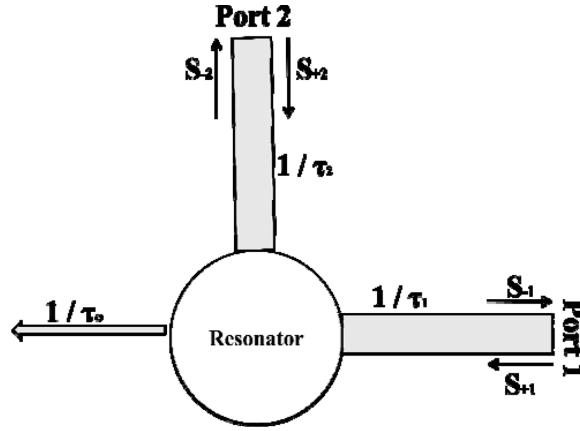


FIGURE 14.2
Theoretical model of L-bend waveguide.

$$a = \frac{\kappa_1 S_{+1}}{j(\omega - \omega_o) + \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_o}}, \quad (14.4)$$

and the incoming and outgoing waves at this input condition are as follows:

$$S_{-1} = -S_{+1} + \sqrt{\frac{2}{\tau_1}} a, \quad S_{-2} = \sqrt{\frac{2}{\tau_2}} a. \quad (14.5)$$

The transmission and reflection coefficients, R_1 and T_2 , of the L-bend waveguide when the system is assumed to be lossless, that is, $1/\tau_o = 0$ becomes

$$R_1 = \left| \frac{S_{-1}}{S_{+1}} \right|^2 = \left| \frac{-j(\omega - \omega_o) + \frac{1}{\tau_1} - \frac{1}{\tau_2}}{j(\omega - \omega_o) + \frac{1}{\tau_1} + \frac{1}{\tau_2}} \right|^2 \quad (14.6)$$

$$T_2 = \left| \frac{S_{-2}}{S_{+1}} \right|^2 = \left| \frac{\frac{2}{\sqrt{\tau_1 \tau_2}}}{j(\omega - \omega_o) + \frac{1}{\tau_1} + \frac{1}{\tau_2}} \right|^2 \quad (14.7)$$

From the above two equations, it can be concluded that at resonance, the transmission is maximum with zero reflection if both the decay rates due to coupling of the waveguide branches with resonator are equal, that is, $1/\tau_1 = 1/\tau_2$. Thus, from the analysis, it is observed that, at the resonant condition, the L-bend waveguide provides higher transmission with zero reflection provided the system is lossless and should have symmetrical properties of the associated ports.

14.3.2 T-Shaped Waveguide

Waveguide plays an important role in the design and development of photonic components and devices to implement integrated photonic circuits. The main use of this waveguide is to split or combine the input light without significant radiation loss. Waveguides with wide-angle branches are subjected to inherent radiation loss at the branching junction. This loss is reduced but not suppressed completely (Foresi et al. 1997; Manolatu et al. 1999) by increasing the refractive index contrast between guiding and cladding regions. Thus, researchers have introduced the design of these wide-angle waveguides using PC, which provides the successful path to eliminate these losses completely (Joannopoulos et al. 1997). In the past decades, researchers have worked on Y-shaped and T-shaped waveguides on PC base among which theoretical considerations have been presented for the latter with near-complete transmission and zero reflection (Fan et al. 2001). In this section, the analysis on T-shaped waveguide is extended to determine its applicability as logic gate with negligible reflection.

T-shaped waveguide is analyzed using the same theoretical model that has been used for the L-bend waveguide, but an extra branch is to be appended. This model seems to be a Y-shaped waveguide as shown in Figure 14.3. In this model, the analysis is done by assuming that the waveguide operates at symmetric condition ($1/\tau_1 = 1/\tau_2$). It means that the ports 1 and 2 are considered to be symmetric and port 3 as asymmetric. In this chapter, the analysis on the T-shaped waveguide is done in three ways and determined the transmission and reflection coefficients to find its applicability in the realization of all-optical logic gates. First, when the asymmetric branch of the waveguide is excited, second, the excitation of any one of the symmetric waveguides and, finally, the excitation of both the symmetric waveguides.

In all the three cases, input ports are excited with electromagnetic signals, and the transmission is observed at the other ports, while the reflection is measured at the same input port or the port that is unused. The profile of the T-shaped waveguide upon exciting the input port(s) for the three cases of analysis is shown in Figure 14.4.

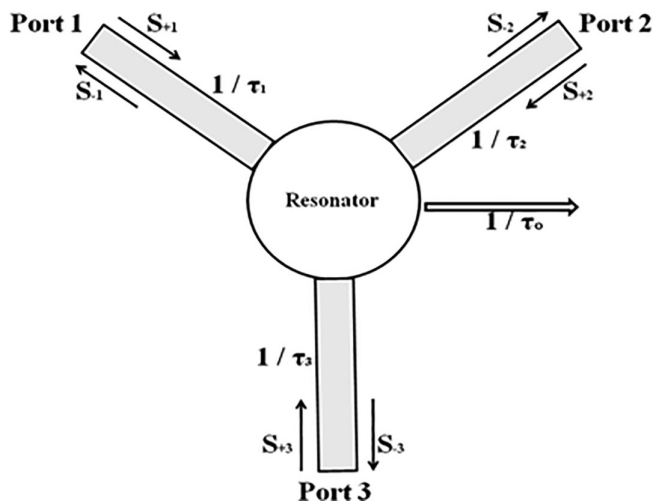
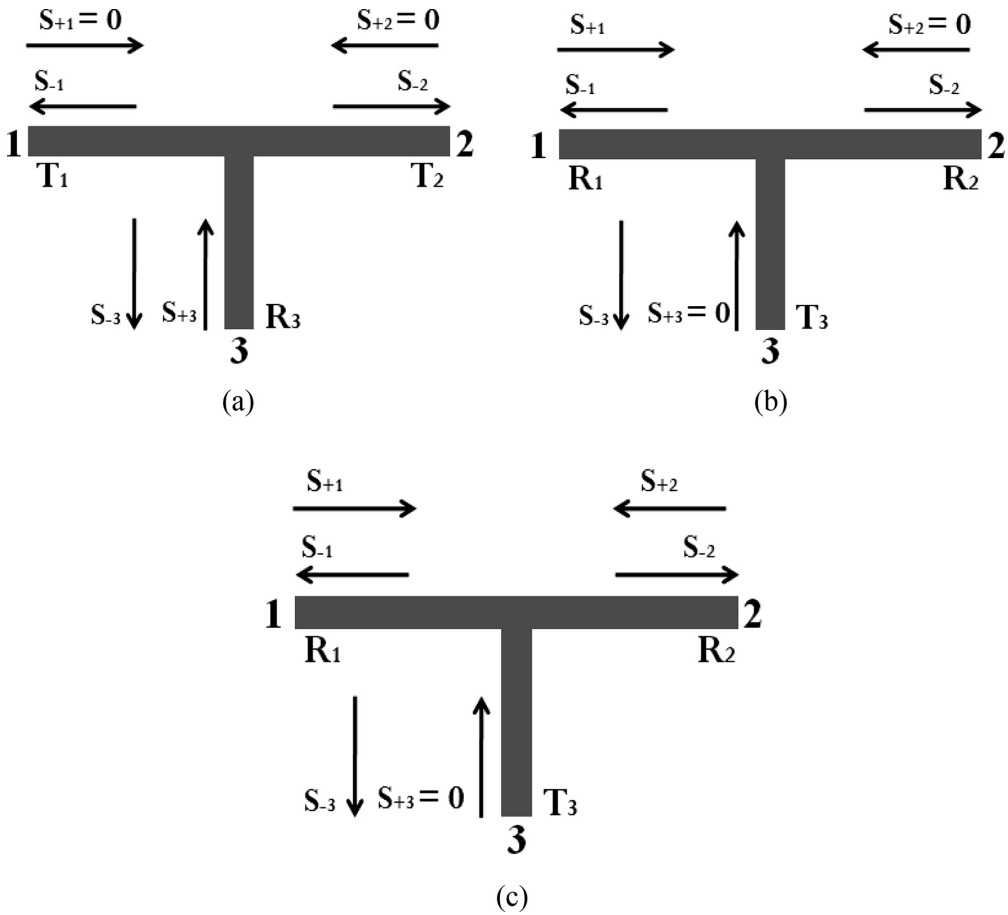


FIGURE 14.3
Theoretical model of T-shaped waveguide.

**FIGURE 14.4**

Profile of T-shaped waveguide upon exciting (a) asymmetric port, (b) one among the symmetric ports, and (c) both the symmetric ports.

In case 1, the asymmetric port 3 is excited with the light signal, and the incident waves at the other ports are zero. The output at ports 1 and 2 is transmission T_1 and T_2 , respectively, with reflection R_3 at the incident port. In case 2, the symmetric port is excited with light signal and so the incident waves at the other ports are zero. The output at the asymmetric port is transmission T_3 with reflection R_1 and R_2 at the other ports. Similarly, in case 3, both the symmetric ports are excited with light signals, and the incident wave at the asymmetric port is zero. So, the output at the asymmetric port is the transmission T_3 with reflection R_1 and R_2 at the other ports. In this analysis of all the three cases, the condition at which the transmission is maximum with low reflection is derived. The analysis that has been done on L-bend waveguide can simply be modified by inserting another decay rate $1/\tau_3$ due to the coupling of third waveguide branch with the resonator. In this analysis, the effect of all these three decay rates is considered when more than one input port is excited unlike the other cases wherein only one port is excited.

Case 1: Excitation of Asymmetric Port of the T-Shaped Waveguide

As it is observed in [Figure 14.4a](#), the excitation of asymmetric port (port 3) may lead to the splitting of input power into two halves. S_{+3} and S_{-3} are the incident and reflected waves with $S_{+1} = S_{+2} = 0$. It is accomplished by assuming that the other two ports are symmetric with each other (Fan et al. 2001). From the analysis of single-port excitation (Fan et al. 2001), the transmission and reflection coefficients, T_1 , T_2 , and R_3 , at this condition are given as follows:

$$T_1 = T_2 = \left| \frac{S_{-1}}{S_{+3}} \right|^2 = \left| \frac{\frac{2}{\sqrt{\tau_1 \tau_3}}}{j(\omega - \omega_o) + \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}} \right|^2 \quad (14.8)$$

$$R_3 = \left| \frac{S_{-3}}{S_{+3}} \right|^2 = \left| \frac{-j(\omega - \omega_o) - \frac{1}{\tau_1} - \frac{1}{\tau_2} + \frac{1}{\tau_3}}{j(\omega - \omega_o) + \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}} \right|^2 \quad (14.9)$$

$$\frac{1}{\tau_1} + \frac{1}{\tau_2} = \frac{1}{\tau_3} \quad \text{Rate matching condition}$$

Both of these expressions show that when the decay rate due to coupling of the branch 3 ($1/\tau_3$) with the resonator is equal to the sum of the decay rates due to coupling of the other two branches ($1/\tau_1 + 1/\tau_2$), the reflection becomes completely zero at resonance. This is called as rate matching condition. It is the condition where the T-shaped waveguide, assumed to be resonant ($\omega = \omega_o$) and symmetric ($1/\tau_1 = 1/\tau_2$), works as a power splitter. This can be experienced by substituting them in expressions (14.8) and (14.9) that transform to Equation (14.10), and this shows that a T-shaped waveguide can very well be utilized as a power splitter at $\tau_1/\tau_3 = 2$ or $\tau_3/\tau_1 = 0.5$ with zero reflection, because the transmission becomes $T_1 = T_2 = 0.5$ at this value. These are the expressions that also preserve the energy conservation:

$$T_1 = T_2 = \left| \frac{2\sqrt{\frac{\tau_3}{\tau_1}}}{1 + 2\frac{\tau_3}{\tau_1}} \right|^2 \quad R_3 = \left| \frac{1 - 2\frac{\tau_3}{\tau_1}}{1 + 2\frac{\tau_3}{\tau_1}} \right|^2 \quad (14.10)$$

Thus, a T-shaped waveguide with the excitation of asymmetric port at resonant and symmetric conditions is used to split the incoming light signal into two halves. This is one of the applications of T-shaped waveguide when there is a need to connect the logic gates in single stage as this type of connection may require splitting of input light, for example, in half adder, wherein the inputs are split to produce *SUM* and *CARRY* outputs.

Case 2: Excitation of One of the Symmetric Ports of the T-Shaped Waveguide

In this case, an attempt is made to check the effect of excitation of one of the symmetric ports on the asymmetric port. Port 1 is being excited with the light signal, and so the incident wave is S_{+1} with S_{-1} as the reflected wave while the incident waves at the other ports, S_{+2} and S_{+3} are zero. The power that reaches out at port 3 is considered to be the transmission T_3 as the main intention of the analysis in this case is to find out the condition at which the transmission is maximum. The power that reaches out to ports 1 and 2 is considered to be the reflection R_1 and R_2 , respectively. The entire notation of the incident and reflected waves along with the transmission and reflection is shown in [Figure 14.4b](#). According to these incident and reflected waves, at symmetric and resonant condition the transmission and reflection coefficients T_3 , R_1 and R_2 would become the following:

$$T_3 = \left| \frac{S_{-3}}{S_{+1}} \right|^2 = \left| \frac{2\sqrt{\frac{\tau_1}{\tau_3}}}{2 + \frac{\tau_1}{\tau_3}} \right|^2 \quad (14.11)$$

$$R_1 = \left| \frac{S_{-1}}{S_{+1}} \right|^2 = \left| \frac{-\frac{\tau_1}{\tau_3}}{2 + \frac{\tau_1}{\tau_3}} \right|^2 \quad (14.12)$$

$$R_2 = \left| \frac{S_{-2}}{S_{+1}} \right|^2 = \left| \frac{2}{2 + \frac{\tau_1}{\tau_3}} \right|^2, \quad (14.13)$$

which also show that the maximum transmission and lower reflection can be achieved at $\tau_1/\tau_3 = 2$ or $\tau_3/\tau_1 = 0.5$. Basically, at port 2, the power that is obtained is considered to be reflection as the effect of excitation of port 1 is only observed at the asymmetric port 3. From these expressions, it is clearly observed that beyond the value of $\tau_1/\tau_3 = 2$, there will be added uneven and higher reflection at ports 1 and 2 with lower transmission at port 3. Thus, at this condition of τ_1/τ_3 , the maximum power can be achieved at asymmetric port with lower reflection at the other two symmetric ports.

In the above two cases, one among the three ports is assumed to be excited with the incident wave wherein the effect of the coupling of only one branch is considered (Haus 1984) as the branches associated with the resonator are independent to each other. However, when more than two ports are to be excited, the resonator branches are assumed to be dependent, which is considered in the next case.

Case 3: Excitation of Both Symmetric Ports of the T-Shaped Waveguide

In this case, both the symmetric ports 1 and 2 of the waveguide are assumed to be excited and observe the effect of it on the asymmetric port 3. The power reaches out to the asymmetric port of the waveguide is considered to be transmission T_3 ,

whereas the power reflected back to the excited ports are R_1 and R_2 . Figure 14.4c clearly shows the incident and reflected waves at each port. As it was discussed previously, the waveguide branches are considered to be dependent on each other when more than one port is excited, the reflected wave S_{-i} changes to the following:

$$S_{-i} = -S_{+i} + \sqrt{2\left(\sum_{i=1}^3 \frac{1}{\tau_i}\right)a}, \quad (14.14)$$

which shows the effect of decay rates of all the three branches. Moreover, the incident waves at the symmetric ports are assumed to be equal in amplitude and phase so that they can have proper interference with each other. As the incident waves are considered to be equal ($S_{+1} = S_{+2}$), the transmission and reflection coefficients are given as follows:

$$T_3 = 2 \left| \frac{S_{-3}}{S_{+1}} \right|^2 = 2 \left| \frac{2\sqrt{2 + \frac{\tau_1}{\tau_3}}}{2 + \frac{\tau_1}{\tau_3}} \right|^2 \quad (14.15)$$

$$R_1 = R_2 = 2 \left| \frac{S_{-1}}{S_{+1}} \right|^2 = 2 \left| \frac{-2 - \frac{\tau_1}{\tau_3} + 2\sqrt{2 + \frac{\tau_1}{\tau_3}}}{2 + \frac{\tau_1}{\tau_3}} \right|^2, \quad (14.16)$$

wherein $S_{+3} = 0$. The transmission and reflection coefficients at the respective ports are derived by summing the coefficients obtained individually upon exciting ports 1 and 2. At the symmetric condition as well as the equivalence of S_{+1} and S_{+2} , the reflected waves S_{-1} and S_{-2} are also considered to be equal. From the above expressions, it is concluded that the transmission at port 3 is maximum (i.e., two, which is considered as the sum of the applied input powers) with zero reflection if $\tau_1/\tau_3 = 2$ or $\tau_3/\tau_1 = 0.5$. Thus, at this condition of τ_1/τ_3 , the T-shaped waveguide can act as power combiner with zero reflection.

From the analysis of all the above cases, it is said that the T-shaped waveguide can split, divert, or combine the applied input power if $\tau_1/\tau_3 = 2$ or $\tau_3/\tau_1 = 0.5$ provided that it works at resonant and symmetric condition. The analysis on the above-said cases is very much applicable to use T-shaped waveguide as logic gate when the symmetric ports 1 and 2 are considered to be the input ports *A* and *B*, and asymmetric port 3 as output port *Y*. For a two input logic gate, if any one of the input ports is excited ($AB = 01$ or $AB = 10$), the output can be either *logic "0"* or *logic "1"*. To achieve *logic "1"* as an output, the analysis of single symmetric port excitation can be used, and for *logic "0"*, the value of τ_3/τ_1 other than 0.5 should be used, which can meet the required output transmission of *logic "0"*. Similarly, in the case of excitation of both the symmetric ports ($AB = 11$), the output should be either *logic "0"* or *logic "1"*. *Logic "1"* can be obtained from analysis of both symmetric ports excitation case while *logic "0"* can be achieved by applying the inputs with out of phase (phase difference of 180°).

14.4 Basic Designs of Logic Gates Using L-Bend, Straight, and T-Shaped Waveguides

In this section, L-bend and T-shaped waveguides are mapped on to the PC, which comprises an array of cylindrical *Si* rods in air host with square-type lattice. The radius (r) of each rod is $0.18a$, where a is the lattice constant of value 540 nm. Line defects are introduced to create L-bend and T-shaped waveguides along with some point defects as directional rods. The waveguide structures are simulated using finite difference time domain (FDTD) method. Before using PC for the creation of waveguides, its PBGs are calculated using plane wave expansion (PWE) method, whose resultant band diagram is shown in Figure 14.5. According to the band diagram, the PC that is used for the design of T-shaped waveguide supports two PBGs of transverse electric (TE) mode. Between them, only one band is selected that ranges from $0.2993 (a/\lambda)$ to $0.4414 (a/\lambda)$, that is, 1223 to 1804 nm, and this band accommodates 1550 nm where the loss is very less. PBG in PC varies with respect to change in the material used, shape of the rods or holes in the crystal, type of the lattice, and so on. Basically, in the analysis, PCs are always considered to be perfect periodic structures. Same way as doping in semiconductor materials for the design of electronic devices, PCs are also subjected to the insertion of defects to implement specific optical functions. Defect is nothing, but the change in structural parameters of the crystal such as change in the material used, the shape of the rods or holes in the crystal, and the type of the lattice. These defects may be localized or extended, which causes disruption in the periodicity of the PC (Joannopoulos et al. 1995). As soon as the periodicity of the PC is disrupted due to the insertion of defects, the translational symmetry would disappear, and the Bloch modes will no longer be the solutions of Maxwell's equations (Joannopoulos et al. 1995). The PC with point and line defects is used as a resonator and a waveguide, respectively; also a uniform PC is used as a reflector as it provides PBG (Joannopoulos et al. 1995).

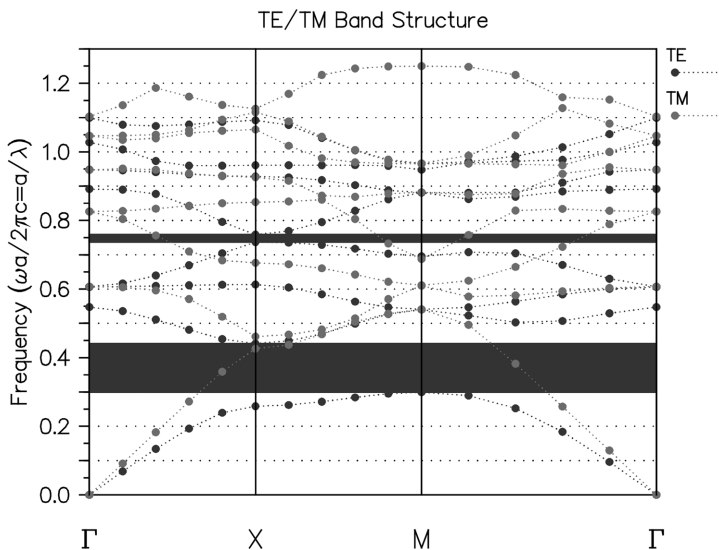


FIGURE 14.5
Band diagram of the uniform photonic crystal.

In order to simulate the structures, input light is launched with Gaussian profile at 1550 nm. To absorb the waves and avoid the reflections at the boundaries, simulation has been done by using perfectly matched boundary conditions. The electromagnetic waves propagate in the (x, z) plane and the magnetic field polarization has been chosen in such a way that it is parallel to the axis of the Si rods, that is, y -axis. The FDTD method must solve the Maxwell's equations by discretizing the fields into space and time. Space grids are chosen such that $\Delta x < \lambda/10$ and $\Delta z < \lambda/10$, to ensure convergence in the simulation, where x - and z -axes are the horizontal and vertical direction coordinates, respectively. To obtain stable simulations, the space grid and the time grid are chosen in order to satisfy the following Courant condition (Wu et al. 2012):

$$c\Delta t < \frac{1}{\sqrt{(\Delta x)^{-2} + (\Delta z)^{-2}}} \quad (14.17)$$

where c is the speed of light in free space.

14.4.1 Straight and L-Bend Waveguides

As and when the defect is inserted, the periodicity disrupts and leads to the disappearance of translational symmetry. Due to this reason, the PC with defects can work as a resonator, waveguide, and so on. The point defect can trap the light, whereas the line defect can allow the light to propagate through an area where the translational symmetry disappears. The line defect acts as a waveguide with light confinement by the edges of that waveguide. Because the remaining part of the PC beyond that waveguide area, which has been created inside, still experiences periodicity and observes the translational symmetry. Thus, there will be no chance for the light to escape from the sides of the waveguide.

Figure 14.6 shows the lattice structure and electric field distribution of the waveguide and also transmission of light over the C-band. From the transmission plot, it is observed that the transmission is near to the input what it was applied and over the C-band, it varies by 10%. Also, the plot represents that the PC-based waveguide propagates light freely through itself as it is observed in the electric field distribution shown in Figure 14.6b. L-bend waveguide analyzed in the previous section shows that a complete transmission can be possible if the properties of the branches connected to the resonator are same. The bend waveguide with such properties is created in the PC with sharp and smooth bends as shown in Figure 14.7. In these waveguides, the physical structure of the branches is quite same vertically and horizontally. Thus, the excitation from any side of this waveguide provides the same output performance. As it is designed with PC, the light at the tight corners cannot escape and lost because it does not depend on the TIR (Joannopoulos et al. 1995). In contrast, the light at the sharp bends of fiber optic cable escapes as they rely on *TIR*, and in order to overcome this, the angle of incidence is made too large.

The L-bend waveguides shown in Figure 14.7 are created with sharp and smooth bends. The difference in the output transmission of both of them in the C-band can be observed from the plot, which is also shown in the same figure. The smooth bends provide higher transmission than the sharp bends, and it is evident. Due to this, the fiber optic cables have smooth curvature. From the plots shown, the transmission beyond 1500 nm wavelength is above 0.74 and below 0.65 in the waveguide with smooth and sharp bends, respectively. In both the cases, reflection is negligible as it was analyzed in the previous section.

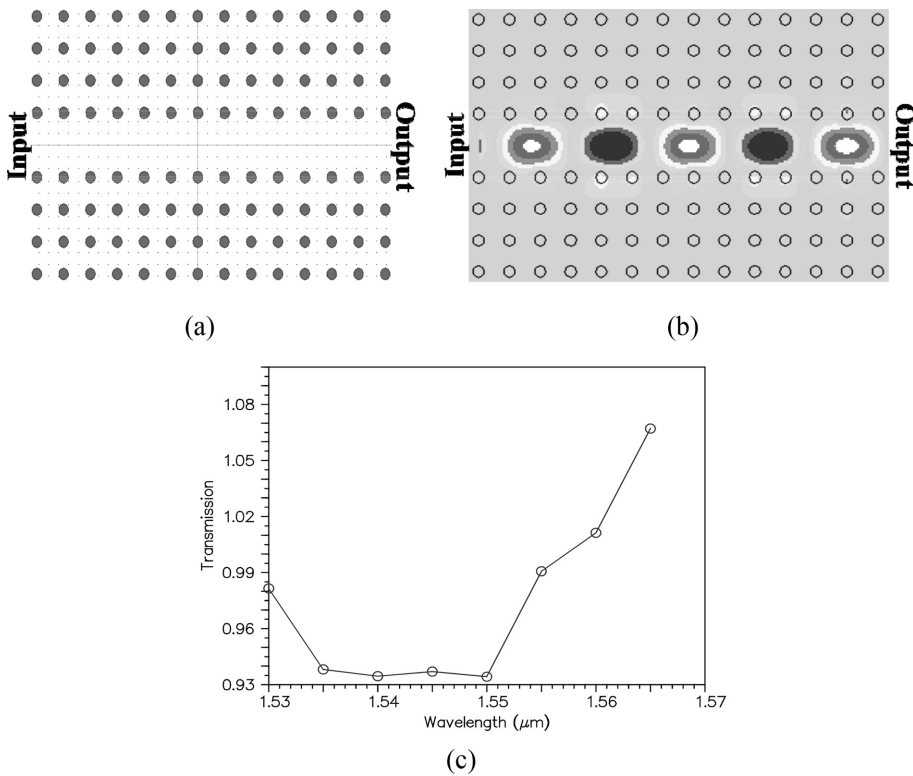


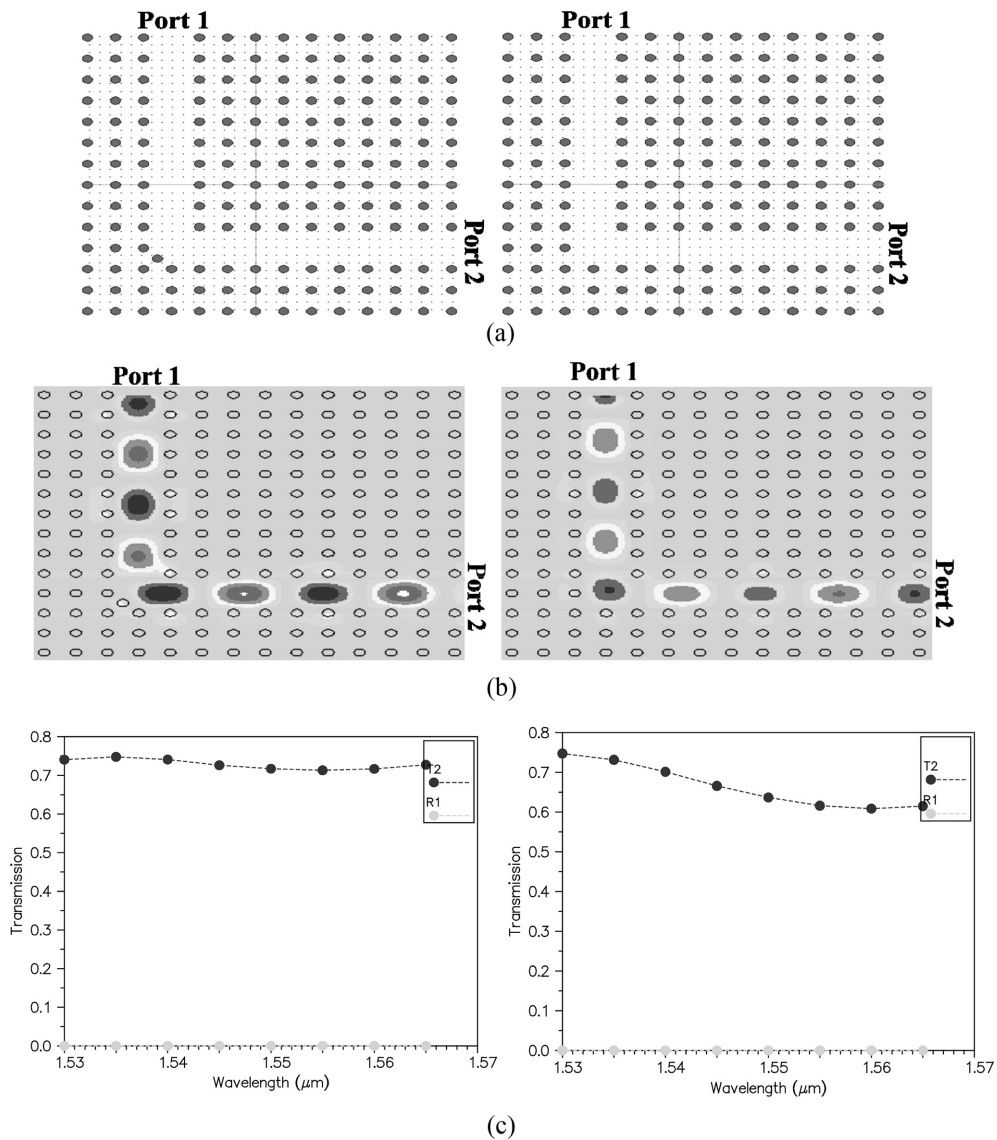
FIGURE 14.6 Straight waveguide (a) lattice structure, (b) electric field distribution, and (c) transmission over C-band.

The electric field distribution in the L-bend waveguide is also shown in [Figure 14.7b](#), wherein it can clearly be seen that the intensity in the smooth bends is higher than sharp bends. These are the bends that are mainly required in the applications where there is a need to allow the light to pass with same bends and interfere perfectly.

14.4.2 PC-Based T-Shaped Waveguide

14.4.2.1 Simulation of PC-Based T-Shaped Waveguide for All the Three Cases of Analysis

The difference between L-bend and T-shaped waveguides is an extra waveguide branch in the latter. For the design of two input logic gates, the waveguide with three branches is required so that the two branches among them can be used as input ports and the other as output port. Thus, the T-shaped waveguide is expected to be useful as a logic gate, as it consists of three ports among them two are symmetric. The T-shaped waveguide created on PC is shown in [Figure 14.8](#), and it is simulated for all the three cases of analysis and observed that it is on par with that. The additional rods R_{s1} and R_{s2} at the junction are optimized to $0.4r$ and $0.25r$, respectively. At these radii values, the PC-based T-shaped waveguide provides the desired output for all the three cases of analysis. The performance of the T-shaped waveguide over the C-band (1530–1565 nm) in these three cases is shown in [Figure 14.9](#), and the transmission and reflection notations given in [Figure 14.4](#) are also observed here. The plot given in [Figure 14.9a](#) is for case 1, wherein transmission of 0.5

**FIGURE 14.7**

Waveguides with smooth (left) and sharp (right) L-bends (a) lattice structure, (b) electric field distribution, and (c) transmission over C-band.

(T_1 and T_2) is observed with minute variation over the C-band, and at 1550 nm, an exact value of 0.5 is achieved. In this figure, the plots for T_1 and T_2 coincide with each due to equal power split at ports, 1 and 2. The transmission at 1530 nm is also same as 1550 nm, that is, 0.5 with the low reflection (R_3) at the former instant. However, the wavelength of 1550 nm is selected because the performance of the T-shaped waveguide at this wavelength is quite better for the remaining cases. Similarly, the plot in Figure 14.9b gives the performance of the waveguide with respect to case 2. In this plot, it is clearly observed that the transmission (T_3) of 0.5 and reflection (R_1 and R_2) of nearly 0.25 is achieved at respective ports on exciting them with the light signals at the wavelength of 1550 nm. In Figure 14.9c,

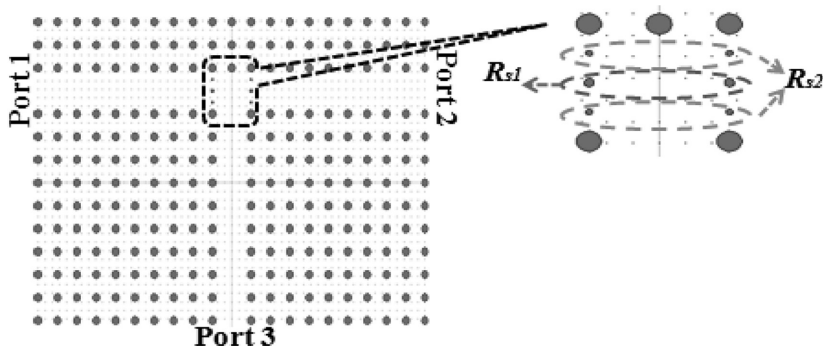


FIGURE 14.8
Lattice structure of T-shaped waveguide-based logic gate structure.

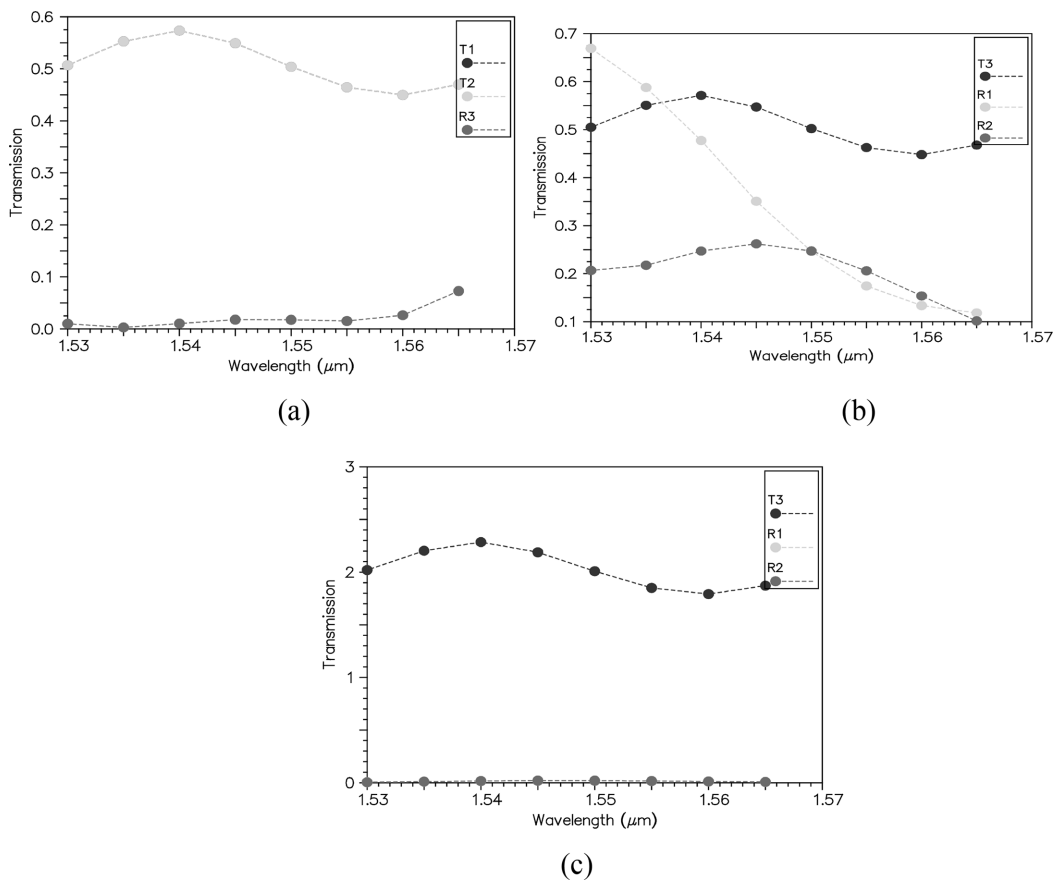


FIGURE 14.9
Performance of the T-shaped waveguide in all the three cases of excitation of (a) asymmetric port, (b) one among the symmetric ports, and (c) both the symmetric ports.

the plot is shown for case 3 wherein a transmission (T_3) of nearly 2 can be observed at a wavelength of 1550 nm with a minute variation over C-band, and the reflection (R_1 and R_2) is low. The plots of reflection coincide with each other as they are same in values. The electric field distribution of the T-shaped waveguide is also shown in Figure 14.10 for these three cases.

When the symmetric branches of the waveguide are excited (case 3) with light signals at zero-phase difference as shown in Figure 14.10a, the transmission at output port 3 is 1.972 with a reflection of 0.00995 at both the input ports A and B, which is due to the constructive interference occurred at the junction. If the phase difference between them is 180° , both the light signals interfere destructively with each other and produce a transmission of 10^{-6} at port 3 as shown in Figure 14.10b. When any one of the symmetric branches of the waveguide is excited with the light signal (case 2), the maximum power is transferred to port 3. The transmission observed is 0.493 with a reflection of 0.25 and 0.1585 at ports 1 and 2, respectively, as shown in Figure 14.10c. Finally, when the asymmetric port 3 is excited with the light signal (case 1), it splits into two halves and produces a transmission of 0.496 at ports 1 and 2 with a reflection of 0.0106 at port 3, and its field distribution is shown in Figure 14.10d.

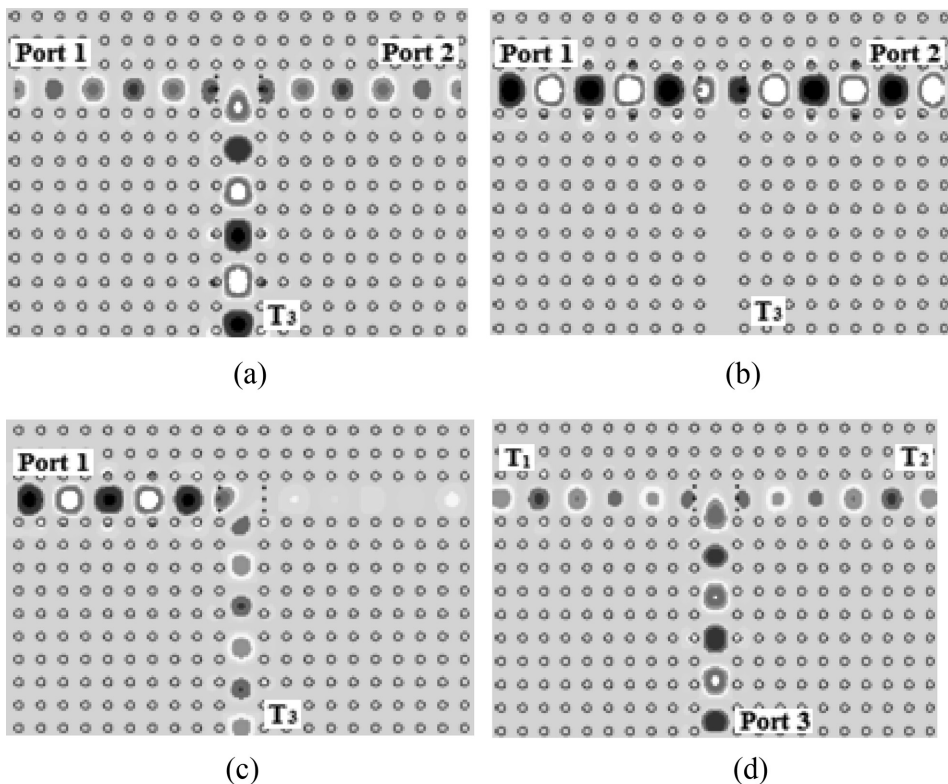


FIGURE 14.10

Electric field distribution of the T-shaped waveguide upon the excitation of (a) both the symmetric ports with zero-phase difference, (b) both the symmetric ports with 180° phase difference, (c) only one symmetric port, and (d) asymmetric port.

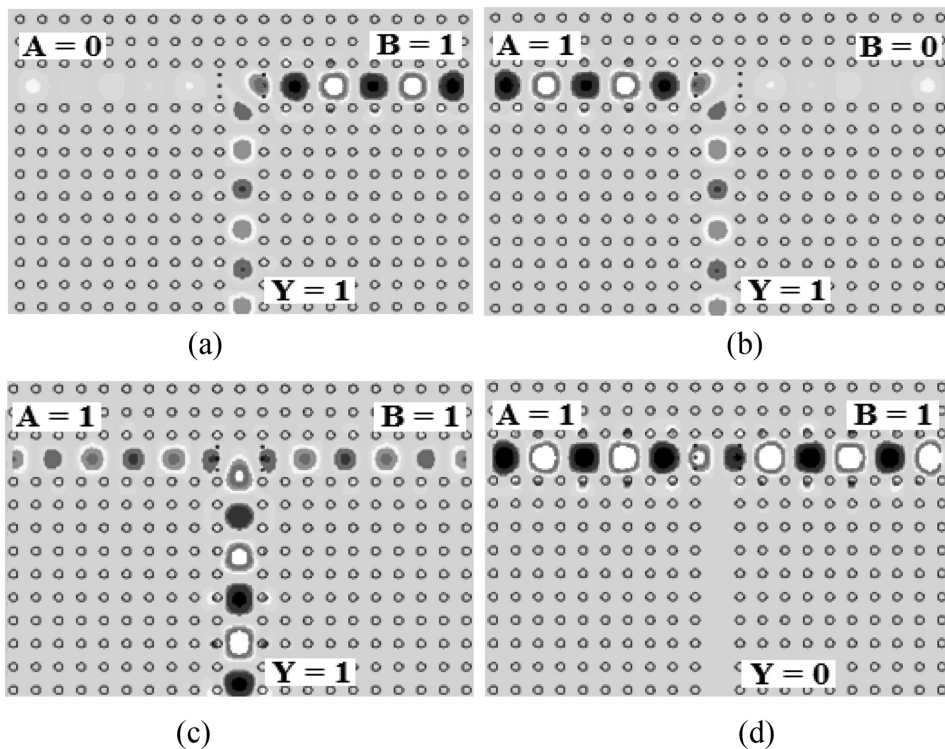
With all these simulated values, it can be clearly witnessed that the PC-based T-shaped waveguide with the structural parameters of $r = 18a$, $a = 540$ nm, $R_{s1} = 0.4r$, and $R_{s2} = 0.25r$ suits well with the analysis done in the previous section. The values that were achieved here match with the values obtained from the analysis of the T-shaped waveguide. Thus, the waveguide shown in [Figure 14.8](#) is analyzed as a two input logic gates, and it is also used to realize the logic functions in single and double stages, which will be discussed in the following section.

14.4.2.2 PC-Based T-Shaped Waveguide as Logic Gate

The analysis of PC-based T-shaped waveguide has been carried out well in the previous subsection for all the three cases of analysis. This conveys that, the waveguide can very well be utilized as logic gate as these are the functions that can mostly be observed in the operation of logic gates. In optical-based logic designs, light and no light are considered as *logic "0"* and *logic "1,"* respectively. However, this cannot be true at the output section of any optical system, because the internal processing of the system does not leave the output to have zero intensity (no light). Thus, at the output section of any optical logic structure, a low intensity is considered to be *logic "0"* and a high intensity is considered to be *logic "1."* In this chapter, only those power levels are considered to be *logic "0"* and *logic "1,"* which provide the contrast ratio of more than 5 dB.

For all the input combinations of two-input logic gates, the output will be either *logic "0"* or *logic "1."* This can be achieved for most of the combinations with T-shaped waveguide using three cases of analysis presented in the previous section, and to acquire this, the ports 1, 2 and 3 are labeled as *A*, *B*, and *Y*, respectively. However, for few input combinations, the required output can be achieved with structural variations such as changing the radius of additional rods available at the junction, making provision to accommodate extra input ports to act as light source and so on. For example, case 2 of the analysis is used to produce the output of *logic "1"* for the input combination of either $AB = 01$ or $AB = 10$ (here *A* and *B* are assumed as input ports and *Y* is assumed as output port). In order to produce *logic "0,"* the radius of the additional rods is to be varied, but this increases the reflection into the unemployed input ports (Shaik and Rangaswamy 2017c), which is undesired as it affects the stability of the system (Wu et al. 2012). However, this kind of structural variation may decrease the contrast ratio because the power level of *logic "0"* is not negligible (Shaik and Rangaswamy 2017c). Similarly, the input combination of $AB = 00$ implies that there is no input excitation, and the required output will be *logic "0."* However, if the required output is *logic "1,"* there is a need to have an extra input port to provide light as a source (e.g., NOT, NOR, NAND, XNOR). Thus, in these kinds of applications, an extra input is used to provide light as a source to produce *logic "1"* at the output. However, this type of approach in the design of logic structures may increase the number of input ports that in turn increase size and response time (Rani et al. 2017).

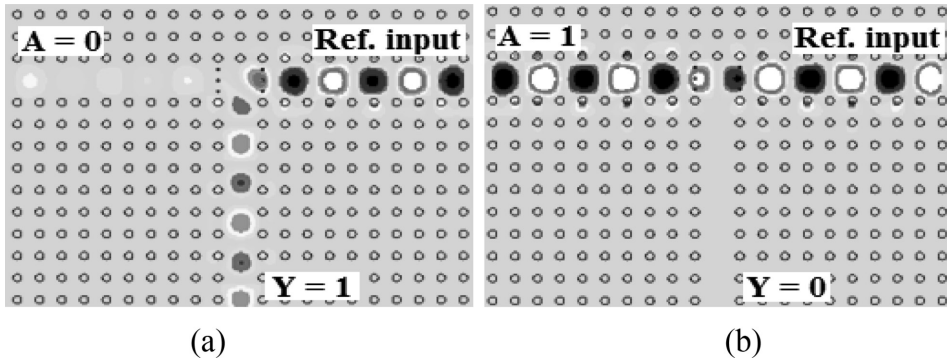
The PC-based T-shaped waveguide explained in this section is described as OR, XOR, and NOT gates, and in order to realize them, the phase of the input light is to be varied. The electric field distribution of the T-shaped waveguide is shown in [Figure 14.11](#), wherein the first two cases are of XOR and OR gates for $AB = 01$ or 10 , and the last two cases are of OR and XOR gates, respectively, for the input combination $AB = 11$. For OR function, the phase of both the input light signals should be same, whereas for XOR and NOT, it is 180° . In OR function, when one of the input ports is excited (symmetric port), the transmission at port 3 is 0.493, which is considered as *logic "1"* per the assumption (case 2 of the analysis). When both the input ports are excited with light signals at same phase values, a constructive interference occurs at the junction and a higher transmission of 1.972 is observed at

**FIGURE 14.11**

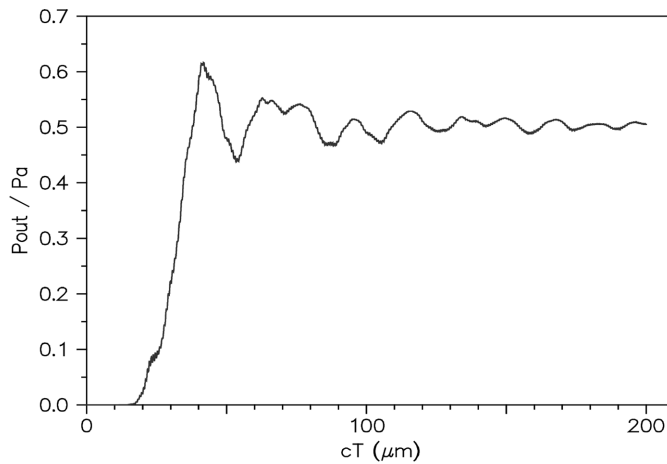
Electric field distribution of the T-shaped waveguide when (a) $AB = 01$ and (b) $AB = 10$ for OR and XOR function, respectively, and $AB = 11$ for (c) OR function and (d) XOR function.

port 3 (case 3 of the analysis). The logical function of the XOR gate is same as that of the OR gate in all the input combinations except $AB = 11$. At this input combination, the output of XOR gate is zero, and in order to achieve this, the phase of one of the input light signals is to be changed to 180° . For this phase difference, destructive interference will occur at the junction, which leads to a transmission of 10^{-6} at port 3.

The operation of T-shaped waveguide as XOR gate can be extended for realizing NOT function. Basically, in the NOT gate, there is only one input and one output, but in optical-based NOT gate, an extra input port is needed to act as a power supply input when input is zero. When input is zero (logic "0"), that is, $A = 0$ (no light), the output Y should be logic "1" (light), which is impossible to achieve. In such a case, there is a need to have an extra input that should act as power supply for logic "1" at port Y . Thus, in the T-shaped waveguide, input B is used as additional input port, which inverts the applied input A . This additional input port B is labeled as reference input (*Ref. input*) whose phase is to be 180° with respect to the actual input applied. When $A = 0$, the reference input takes a turn toward output port Y as logic "1" (case 2 of the analysis). Similarly, when $A = 1$, the reference input will interfere destructively with input A and produces a transmission of 10^{-6} at port Y as logic "0" (case 3 of the analysis). The electric field distribution of the T-shaped waveguide as NOT gate is shown in Figure 14.12. The contrast ratio is calculated from the achieved power level of logic "0" and logic "1," and it is 56.92 dB. This much of higher value of contrast ratio has become possible due to the negligible transmission of logic "0," and perfect destructive interference between the inputs is the basic reason behind this.

**FIGURE 14.12**

Electric field distribution of the T-shaped waveguide as NOT gate when (a) $A = 0$ and (b) $A = 1$.

**FIGURE 14.13**

Time evolving curve of the T-shaped waveguide-based logic gate.

The response period of the proposed AND gate can be calculated using the time evolving curve of the output power (Rani et al. 2013; Wu et al. 2012) as shown in Figure 14.13. From the figure, it is observed that the time required to move from 0% to 90% of the average output power P_{avg} is $T = 0.11984$ ps (or $cT = 35.95$ μm). The time t consists of two components t_1 and t_2 , where t_1 is the time due to transmission delay and t_2 is the time required to move from 0.1% to 90% of the average output power P_{avg} . The time components that can be observed are $t_1 = 0.0497$ ps and $t_2 = 0.07014$ ps. As the entire system operates on the linear material, it is expected that the falling time required to reach from P_{avg} to 10% of P_{avg} is approximately equal to t_2 . So, a narrow pulse of width $2t_2 = 0.14028$ ps can be produced at the output. If the ON time is equal to OFF time, then the response period of the output signal from the AND gate is 0.28056 ps. So, the proposed gate can operate at a bit rate of 3.56 Tbps.

14.5 Single-Stage and Two-Stage Logic Design Analysis

In this section, an attempt has been made to discuss the cascading of logic gates that have been explained in the previous section using PC-based T-shaped waveguide. For such, two T-shaped waveguide-based XOR gates are connected in single stage and observed the results. Similarly, an OR gate and a NOT gate are cascaded (two stages) to determine the NOR function. Upon cascading the logic gates in single stage or double stage, the contrast ratio would be changed, and this is due to variation in the power level of logic values. The power level of logic values would change because of improper interference pattern that occurs due to uneven waveguide structures through which the light signals pass and interfere. This can be observed from the cascaded structures given in the following subsections. In those figures, the input branches of the T-shaped waveguides are modified such that their effect on the interference pattern is less.

14.5.1 Single-Stage Logic Design

The XOR gate described in the previous section is used here for single-stage connection. The schematic of two XOR gates connected in single stage is shown in Figure 14.14a along with its truth table, and its lattice structure is also shown in Figure 14.14b. As input B is common for both XOR gates, a T-shaped splitter has been used to split the input light. In order to accomplish the perfect interference pattern at both the junctions of the XOR gates, input branches A and C of the T-shaped waveguides are extended horizontally. The two-gate single-stage structure is simulated for all the input combinations with light intensity at input B double than the intensity at inputs A and C , as the light at B needs to

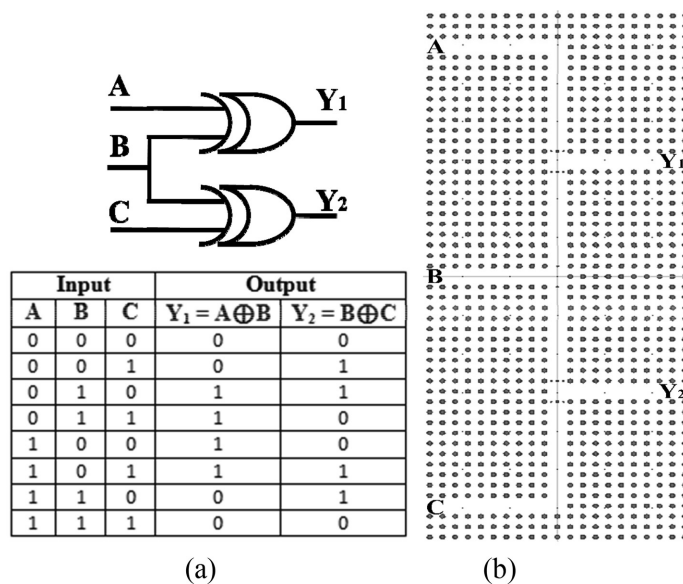


FIGURE 14.14

Single-stage connection of two XOR gates: (a) schematic (up) with truth table (down) and (b) lattice structure.

split. Apart from higher intensity, the phase of input B is also maintained at 180° phase as one of the inputs of the XOR gate should be out of phase.

The two-gate single-stage structure is simulated for all the input combinations, the electric field distribution of the structure is shown in Figure 14.15. From the results obtained, the maximum value of the contrast ratio is of 13.15 dB, which is low. When we compare the contrast ratio of the single-stage structure with the XOR gate, it is said that it is lower nearly by fourfold. The main reason is the improper destructive interference occurs at the XOR gate junction due to uneven waveguide branches through which the input light signals pass. The branch B through which the light signal passes is basically a power splitter, and the branches A and C through which light signals pass are a straight bent waveguide. This has made the light signals to interfere destructively in an improper way. Due to this, the transmission of *logic "0"* is not negligible but a considerable amount. This increase in the power level of *logic "0"* leads to decrease in the contrast ratio of the single-stage structure. This type of effect may surely be on the output of the cascaded structures due to the improper waveguides.

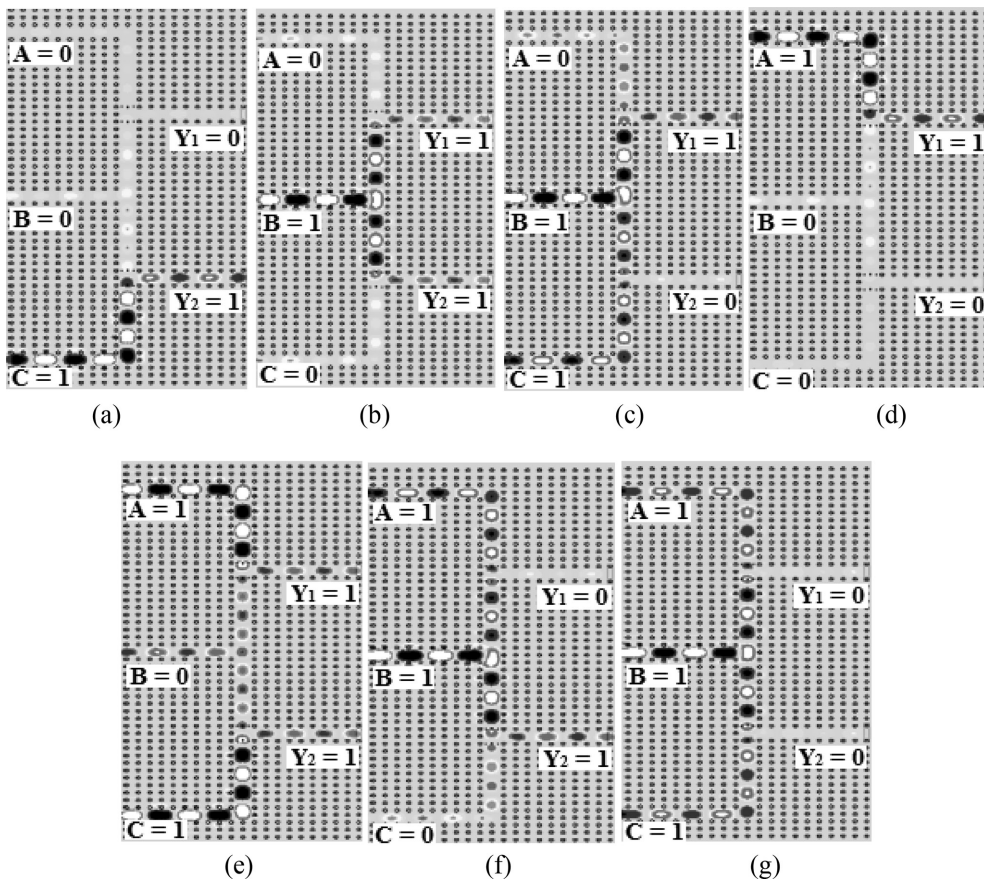


FIGURE 14.15

Electric field distribution in the single-stage structure for input combinations: (a) $ABC = 001$, (b) $ABC = 010$, (c) $ABC = 011$, (d) $ABC = 100$, (e) $ABC = 101$, (f) $ABC = 110$, and (g) $ABC = 111$.

14.5.2 Two-Stage Logic Design

In this section, an attempt is made to discuss the cascading of logic gates in two stage that operates with acceptable contrast ratio. Here, T-shaped waveguide-based OR and NOT gates are cascaded in such a way that the outcome is of NOR. The T-shaped waveguide that has been described in the previous section for specified functions is used in two stages, as OR gate with -90° bend in the first stage and as NOT gate in the second stage. They are cascaded in such a way that the asymmetric port of the OR gate superimposes the input port of the NOT gate, and this way of cascading makes the structure small. The reference input port of the NOT gate in the cascaded structure is extended to have same path length for the *Ref. input* and the inputs *A* and/or *B* of the OR gate to reach the second junction where from the output can be collected. In order to counterbalance, the effect of the additional rods of the OR gate on the final output, the rods with same dimensions are placed in the bend waveguide of the *Ref. input*. The schematic of the cascading of OR gate with NOT gate as well as its truth table is shown in Figure 14.16 along with the lattice structure.

The structure is simulated for all the input combinations shown in the truth table, and the electric field distribution for all these cases is shown in Figure 14.17. For all the input combinations, the *Ref. input* is applied with 180° phase. When the input ports *A* and *B* are unexcited, the *Ref. input* directs toward the port *Y* as output with a transmission of 0.73 as *logic "1."* Upon the excitation of port *B* with light signal, it interferes destructively with the *Ref. input* and provides a transmission of 0.154 as *logic "0."* Same operation happens when port *A* is excited with light signal. Similarly, when both ports *A* and *B* are excited with light signals, they interfere constructively at the first junction and directs to the second junction to interfere destructively with the *Ref. input*. This provides a transmission of 0.0123, which is considered as *logic "0."* The minimum value of the contrast ratio calculated from these logic values is 6.76 dB. From the contrast value obtained, it can very well be said that the cascading of T-shaped waveguide-based logic gates results in logic designs with appreciable results.

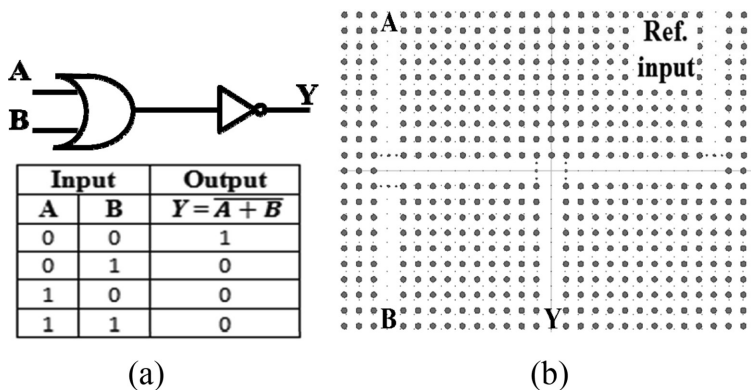
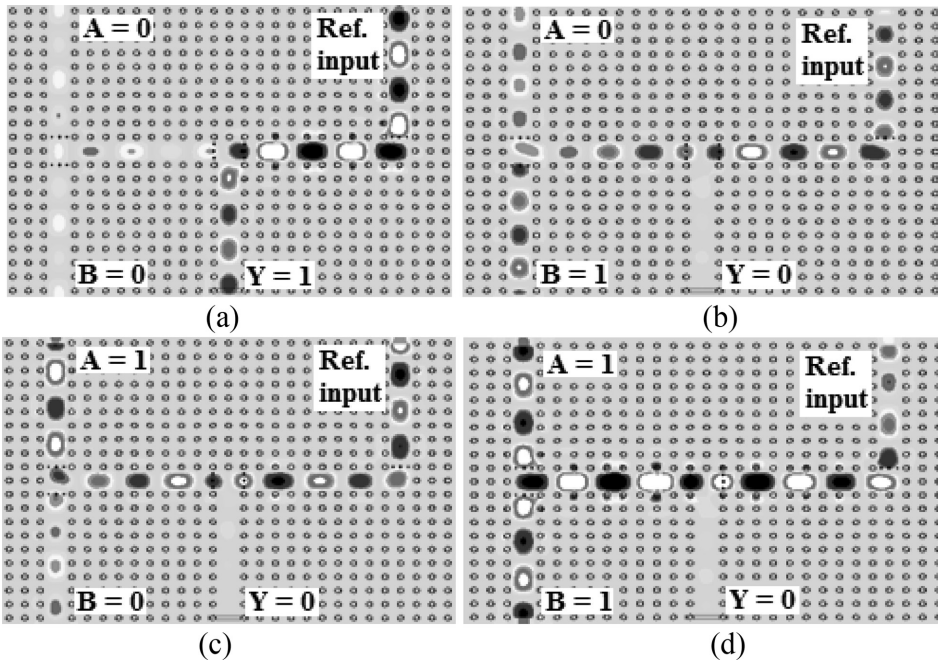


FIGURE 14.16

Two-stage connection or cascading of OR and NOT gates: (a) schematic (up) with truth table (down) and (b) lattice structure.

**FIGURE 14.17**

Electric field distribution in the two-stage structure for input combinations: (a) $AB = 00$, (b) $AB = 01$, (c) $AB = 10$, and (d) $AB = 11$.

14.5.3 Discussion on Response Time of the Single-Stage and Double-Stage Structures

The time-evolving curves of the single-stage and double-stage structures are shown in Figure 14.18. From Figure 14.18a, it is observed that the two time components t_1 and t_2 of a single-stage structure are 0.084 and 0.0887 ps, respectively. When we compare the transmission delay component t_1 of the single-stage two-gate structure with that of T-shaped waveguide-based logic gate, its value is higher, and this is due to the longer distance the input light signals need to pass to reach the output port. The other component t_2 is also higher due to the same reason. From the value of t_2 , the calculated response time is 0.3548 ps, which indicates that the single-stage two-gate structure operates with a bit rate of 2.818 Tbps. Similarly, for the double-stage cascaded structure whose time evolving curve is shown in Figure 14.18b, the transmission delay t_1 is larger as the light signals need to pass through two stages to reach out the output port. The transmission delay t_1 of the double-stage structure is 0.964 ps, which is nearly twofold than that of the logic gate structure. The time component t_2 from which the response time is calculated is around 0.1697 ps, which is also nearly double than that of the logic gate. From this value, the calculated response time is 0.6788 ps, that is, the cascaded structure operates with a bit rate of 1.47 Tbps.

Finally, the response time of single-stage and double-stage structures show that the implementation of double-stage structures using PC-based all-optical logic gates also decreases the speed. The single-stage two-gate structure provides response time higher by 26.46% than the basic T-shaped waveguide-based logic gate, and it is evident. For the double-stage two-gate structure, the response time is higher by 2.42 times than the based logic gate.

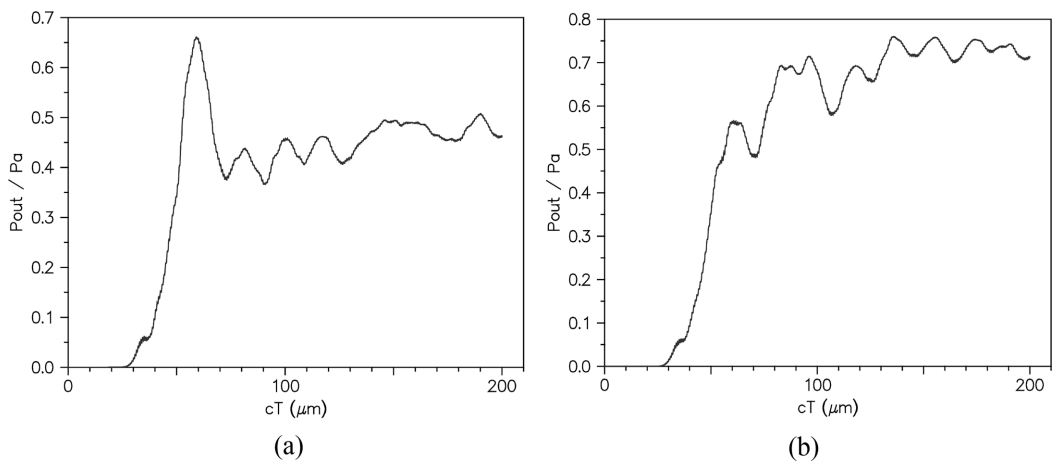


FIGURE 14.18
Time evolving curve of (a) single-stage and (b) double-stage structures.

14.6 Discussion and Conclusion

The bandgap engineering in the PC plays a main role in the design of the waveguide, resonators, and so on, which are the basic components of photonic integrated circuits. This feature has made the PC to work around the sharp bends and wide-angled waveguide with low loss. In contrast, the signal propagation in fiber optic cable or optical waveguide is limited by the wide-angled structures due to signal loss. This could be eliminated but not suppressed completely by designing the waveguide structures with PC. Similar to the performance enhancement achieved in the PC fibers compared with the conventional fibers, the waveguide design on the PC will also provide superior outcome than the optical waveguides or fiber optic cables. The design of the basic components of optical computing systems using PC can make a major breakthrough in the research of photonic integrated circuits. Thus, in this chapter, a suitability of simple T-shaped waveguide as logic gate is explained using CMT and evaluated with PC-based T-shaped waveguide for OR, XOR, and NOT functions.

As the T-shaped waveguide is simple and compact, the response time of the waveguide as logic gate is very less upon applying the inputs, and its value is less than a picosecond. Furthermore, the equal length of the input branches of the T-shaped waveguide with symmetrical properties has provided clear destructive interference because of which the negligible intensity at the output for *logic "0."* The effect of this on the output contrast ratio of the logic gate is high contrast ratio, which is above 50 dB. Due to the higher contrast ratio, the T-shaped waveguide-based logic gates can be connected in single or double stages in order to realize the high-end logic functions. The cascading of PC-based logic gates degrades the contrast ratio due to uneven waveguide branched through which the input light signals pass and interfere. The interference of light signals from this type of waveguide branches leads to improper interference, and thus the contrast ratio would get affected. In order to overcome this, few modifications in the actual designs are made such as insertion of additional defects in the waveguide branches, appending the waveguide branches with bend waveguides, and so on.

Finally, from the logic gate designs and cascading of them with reasonable results, it is said that the logic gate designs using T-shaped waveguide provide better performance in terms of speed, area, and output contrast. However, implementation of high-end logic functions using PC-based logic gates may not provide appreciable result due to the degradation of power levels of logic values. This is overcome by doing advancements in the artificial optical materials specifically to overcome these limitations.

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15

Photonics for Biomedical Sensing

K. P. Swain, G. Palai, and P. Sarkar

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15.1 Introduction

A photonic crystal (PC) is a novel type of optical nanostructures where the motion of photon particles is affected in similar way of electron in a semiconductor crystal, which deals with an electronic bandgap analogous to the photonic bandgap (PBG), where PBG leads to realize various applications pertaining to various types of artificial structure. As far as reality is concerned, the notion of a PC is found in 1887 (Rayleigh 2009) by English Physicist Lord Rayleigh’s experiment with periodic multiple dielectric stacks, where he showed PBG in one direction. After that, none of the researchers would take interest in this field due to take away from realization. However, two papers published by Eli Yablonvitch and Sajeev John around the year 1988 (John 1987; Yablonovitch 1987) brought an interest to all photonic researchers to carry out a new type of research in the field of photonics. In their research, periodic structures with more than one dimension have been disclosed called the PC, which occurs in nature in the form of structural correlation and animal reflection and in different forms, which promises. For example, the wings of some butterflies

contain a periodic structure in such a way that it belongs to the photonic crystal structure (PCS). Similarly, the natural periodic microstructure of opal in the bracelet is responsible for bright colors and, essentially, belongs to the regular periodic arrangement and category of the PC. For this, a good example of these is the structure of the barbules of brightly colored birds. The best-known and spectacular example may be the green peacock. To realize the same, the following few color pictures have been collected from different sources and mentioned in Figure 15.1.

Considering the natural PCS, Figure 15.1f is the common magpie (*Pica*) usually appeared in black and white. However, it shows two types of brightness under appropriate illumination and view angle. Interestingly, it is shown that both tail and wings of its feather's reflection are arranged in a regular manner, which would be the property of the periodic crystal. As far as the natural structure and application of the photonic device are concerned, it can be fabricated in one, two, and three dimensions. One-dimensional PCs can be made of the layer by layer stuck together in one dimension only, where the process of photolithography or by etching holes plays the vital role in designing 2D PCS. Further, the stacking of multiple 2D layers gives a three-dimensional photonic structure, which can be drilled or etched under different angles using direct laser writing as shown in Figure 15.2a.

In Figure 15.2a, it is shown that one-dimensional PCS consists of different dielectric constants, which may be deposited or adhered to form bandgap in a single direction. A Bragg grating is an example of a one-dimensional PC. One-dimensional photonic structure can be an isotropic or anisotropic in nature, where the latter can be used as an optical switch. As far as the current research scenario pertaining to different dimensions of photonic crystal fiber (PCF) is concerned, the fabrication, design, application, and marketing with respect to one-dimensional PCS has already been reached

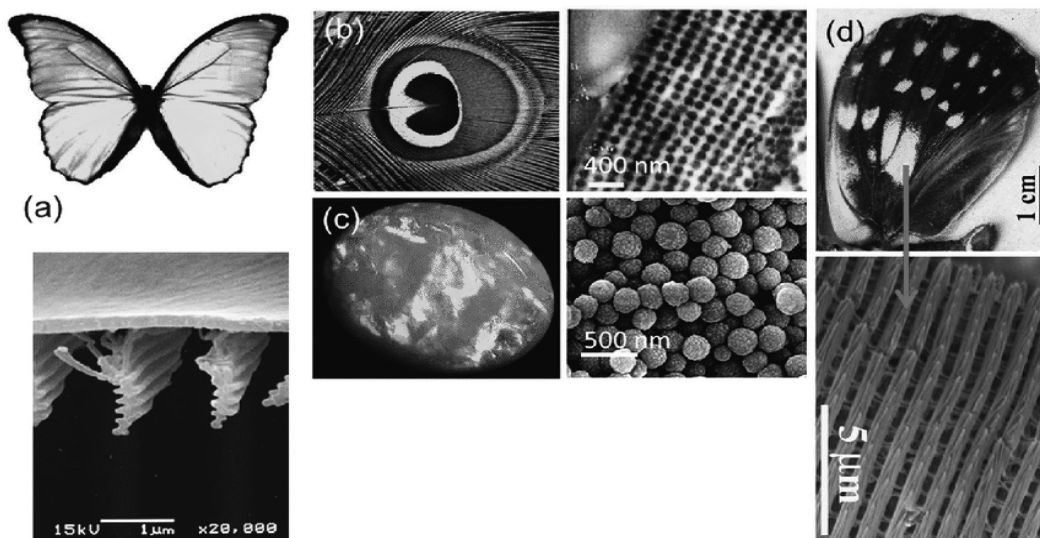
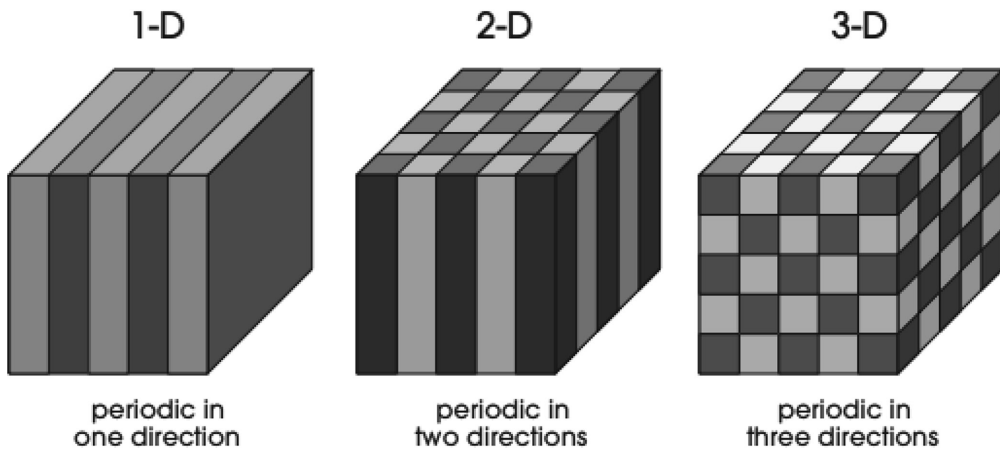


FIGURE 15.1

Different examples of natural photonic crystals as (a) Morpho butterfly, (b) multi-colored peacock feather, (c) natural opal gemstone and (d) wing of *Sasakia Charonda* with their microscopic images. (From Armstrong, E. and O'Dwyer, C., *J. Mater. Chem. C.*, 3, 6109–6143, 2015.)

**FIGURE 15.2**

One-, two-, and three-dimensional photonic crystal structures. (From Joannopoulos, J.D. et al., *Photonic Crystal: Modeling of Flow of Light*, Princeton University Press, Princeton, NJ, 1995.)

the mature stage, whereas in the case of 2D PCS, the same is undergoing and is at a younger stage, not attained mature stage so far. However, the research on 3D PCS is sluggish due to its fabrication feasibility. As shown in [Figure 15.2b](#), two-dimensional PCS can be fabricated by etching in a regular air hole on the substrate. Different types of 2D PCSs can be realized, such as square, triangular, and honeycomb PCs. The holey fiber of PCS is a suitable example of the 2D PCS. It is shown that 3D PCS is similar to 2D PCS except stacking, that is, the latter shows stacking in two directions, whereas the former shows stacking in three directions. Different types of 3D PCS can be realized such as yablonovite, the woodpile structure, inverse opal structure, and a stack of two-dimensional crystal. Although the above-said statement discloses various types of the PCS with their properties, a higher dimensional PCs encounter fabrication challenge pertaining to enough precisions to prevent enough scattering property and robustly mass production crystals. As far as two-dimensional PCS is concerned, one promising method to develop a PC is fiber drain technique. Another technique is used to make a pattern on slabs, which provides the potential to combine photonic processing with electronic processing in a single chip. Considering three PCSs, various techniques have been used including photolithography and etching technique similar to those of photonic integrated circuits. Again considering the intrinsic mechanism of PCS, the operational mechanism depends on the PBG of the PCS. To compute the PBG of the structure, normally we deal with various types of computational mechanisms such as finite element method, finite difference time domain method, plane wave expansion (PWE) method, KKR method, Bloch wave method, and construction of the bond diagram method. Apart from this, the PWE method is used for a simple photonic structure where simple refers to no defect in it. The band structure of the PC is computed using the Eigen formulation of the Maxwell equation and those solving eigen frequencies or each of the propagation direction of the wave vectors. It solves not only the dispersion diagram but also the magnitudes of bandgap corresponding to the same. Moreover, all works deal with the PWE method in this chapter, which is clearly described in the next sections.

15.2 Computational Mechanism for “PWE” Technique

As far as mathematical formulation of PWE method is concerned, it is easy to implement because the technique is simple and gives accurate results pertaining to homostructure of PC, where homostructure manipulates with a periodic structure without any defect. To derive its equation, one should use Maxwell's electromagnetic equation. The components of these equations can be written as follows:

$$\frac{\partial}{\partial x} E_y - \frac{\partial}{\partial y} E_x = -\frac{1}{c} \frac{\partial}{\partial t} B_z \quad (15.1)$$

$$\frac{\partial}{\partial x} E_y - \frac{\partial}{\partial y} E_x = -\frac{1}{c} \frac{\partial}{\partial t} B_z \quad (15.2)$$

$$\frac{\partial}{\partial y} H_z = \frac{1}{c} \frac{\partial}{\partial t} D_x \quad (15.3)$$

$$-\frac{\partial}{\partial x} H_z = \frac{1}{c} \frac{\partial}{\partial t} D_y \quad (15.4)$$

$$\frac{\partial}{\partial y} E_z = -\frac{1}{c} \frac{\partial}{\partial t} B_x \quad (15.5)$$

$$-\frac{\partial}{\partial x} E_z = \frac{1}{c} \frac{\partial}{\partial t} B_y \quad (15.6)$$

$$\frac{\partial}{\partial x} H_y - \frac{\partial}{\partial y} H_x = \frac{1}{c} \frac{\partial}{\partial t} D_z \quad (15.7)$$

Using these equations, a simplified term corresponding to transverse electric and transverse magnetic modes of propagation can be represented as follows:

$$\frac{1}{\varepsilon(r)} \nabla \times \{ \nabla \times E(r) \} = \frac{\omega^2}{c^2} E(r) \quad (15.8)$$

$$\nabla \times \left\{ \frac{1}{\varepsilon(r)} \nabla \times H(r) \right\} = \frac{\omega^2}{c^2} H(r) \quad (15.9)$$

As Equations (15.1) and (15.2) deal with PWE, let us assume that the solutions of equations are as follows:

$$E(r) = E_{kn}(r) e^{ikr} \quad (15.10)$$

$$H(r) = H_{kn}(r)e^{jkr} \quad (15.11)$$

Again considering the periodicity of the crystal with respect to different axial direction and realization of periodicity of electric field, it can be expressed as follows:

$$E_{kn}(r + R) = E_{kn}(r) \quad (15.12)$$

$$H_{kn}(r + R) = H_{kn}(r) \quad (15.13)$$

Furthermore, considering the permittivity of dielectric column can be expressed as follows:

$$\frac{1}{\varepsilon(r)} = \sum_G \chi(G) \exp(jGr) \quad (15.14)$$

Reuniting the above-said equations, the final expression can be written as follows:

$$\sum_{G'} \chi(G - G') (k + G') \times \{ (k + G') \times E_{kn}(G') \} = \frac{\omega_{kn}^{(E)^2}}{c^2} E_{kn}(G) \quad (15.15)$$

$$\sum_{G'} \chi(G - G') (k + G) \times \{ (k + G') \times H_{kn}(G') \} = \frac{\omega_{kn}^{(H)^2}}{c^2} H_{kn}(G) \quad (15.16)$$

Moreover, considering two-dimensional PCS, the equation for light propagation can be expressed as follows:

$$-\left\{ \frac{\partial}{\partial x} \frac{1}{\varepsilon(r_{\parallel})} \frac{\partial}{\partial x} + \frac{\partial}{\partial y} \frac{1}{\varepsilon(r_{\parallel})} \frac{\partial}{\partial y} \right\} H_z(r_{\parallel}) = \frac{\omega^2}{c^2} H_z(r_{\parallel}) \quad (15.17)$$

$$-\frac{1}{\varepsilon(r_{\parallel})} \left\{ \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right\} E_z(r_{\parallel}) = \frac{\omega^2}{c^2} E_z(r_{\parallel}) \quad (15.18)$$

Using similar type of consideration, the final equation for TE and TM polarization modes of propagation is given by the following:

$$\sum_{G_{\parallel}} \chi(G_{\parallel} - G'_{\parallel}) |k_{\parallel} + G'_{\parallel}|^2 E_{z,k_{\parallel}n}(G'_{\parallel}) = \frac{\omega_{k_{\parallel}n}^{(E)^2}}{c^2} E_{z,k_{\parallel}n}(G_{\parallel}) \quad (15.19)$$

$$\sum_{G_{\parallel}} \chi(G_{\parallel} - G'_{\parallel}) (k_{\parallel} + G_{\parallel}) (k_{\parallel} + G'_{\parallel}) H_{z,k_{\parallel}n}(G'_{\parallel}) = \frac{\omega_{k_{\parallel}n}^{(H)^2}}{c^2} H_{z,k_{\parallel}n}(G_{\parallel}) \quad (15.20)$$

Using Equations (15.15), (15.16) and (15.19), (15.20), the band structure of PC can be computed.

15.3 Literature Review for Application of Photonics

Mostly in civil engineering, fiber Bragg grating (FBG) sensor is used to monitor the constructional fitness of building, bridges, and so on. The electronic sensors are subject to failure if used for a long period as decaying process of civil structures is very slow over time. Hence, Martone et al. (2014) discussed how optical sensors with robust algorithm are preferred for accurate and reliable measurement. The most beneficial properties of FBG sensors are resistant to electromagnetic interference, small dimension, and light weight. It can also be embedded inside the structure where possible deformation and dynamic response are likely possible. The principle of FBG is the reflected signals, which can be demodulated for measurement process.

FBG-based optical sensors can also be used in a variety of multiplexing techniques with different modulation formats such as WDM, TDM, FDM, coherence multiplexing (CM), and the polarization division multiplexing (PDM). Especially, two optical sensors based on FBG are used for structural health monitoring such as accelerometers and inclinometers. In accelerometers, the grating wavelength shift is calibrated according to the level of acceleration. The shifting of grating wavelength depends on the vertical movement of an internal mass when exposed to external acceleration.

The inclinometers are widely used in tunnels, foundation, and platform leveling to watch the ground movement. The sensors are used to measure the angular tilt with respect to an artificial horizon generated by it. FBG sensors can also be used to monitor the land slide and tunnel stability, rock deformation, ground movement as it has the important advantage of being resistant for Electromagnetic interference (EMI) and resistant to corrosion and water damage.

Different types of optical sensors are discussed by Riccio (2014), which are mostly used to measure the solar energy reflected by the earth surface. Based on the resolution and coverage area, the sensors in this group are categorized into the following groups: the low order of 100-m sensors is mainly used for forest, coastal, ocean monitoring, agriculture application, and desertification assessment; the medium order of 10 m of resolution sensors is used for monitoring of land and ocean over a wide area and also for security application; and third category of high resolution (order of meters) is used in local area to monitor specific applications such as security and emergency applications.

Radio meters is a passive sensor used to monitor the thermal emission from land, emission, and dielectric constant of surface, whereas spectrometers are used to monitor the chemical factor involved in atmosphere. Altimeters are used for monitoring the local features on solid earth, sea level, and marine ice position and composition. Scatterometers, which are an active sensor and worked on microwave frequency, are used to estimate the wind pattern over the ocean and also support the altimeter data for the precise measurement.

Photonic technique plays an important role in safety and security issue in cultural heritage fields. Cucci and Tornari (2014) have discussed the different passive sensors, which are used to monitor the impact of different environment factors such as temperature, humidity, UV radiation, light on various artworks on museum wall and galleries. One of the most important optical fiber-based sensor is calorimetric-passive sensor. FBG sensors are also used to control the stress and strain in wooden artwork. Fiber optics reflectance spectroscopy (FORS) is also used for performing the noninvasive diagnostics for various categories of artwork.

Di Pasquale et al. (2014) suggested how Raman-based distributed temperature sensors (RDTs) are mostly used for industrial applications to detect the fire in plants and tunnels

and also for detection of leakage in pipelines of oil or gas industries. RDTS has the most advantages that it can be successfully used in extreme environmental condition where EMI is a major issue. The principle of RDTS is based on the optical time domain reflectometry (OTDR), which depends on the measurement of backscattered Raman anti-Stokes signals.

The main application of RDTS is to detect fire in long tunnels of railways and highways, cable trays, warehouses, car parking places, and large hotels as it is capable of measuring over long distances by operating in loop configuration. Generally, a Complementary metal–oxide–semiconductor (CMOS) chip is used to read the sensor output. RDTS along with the modern information and communication technology (ICT) can also be effectively used to monitor the reservoirs, wellbores, pipelines, and power cables and to measure the temperature profile of oil and gas pipelines and geothermal wells.

Photonics and spectroscopic techniques are used as an excellent tool for safety and security because of their capacity to investigate the matter at a structural level. These can be used efficiently to detect the explosive materials, drugs, and biological and chemical warfare agents (weapons of mass destruction). There are many modes and types discussed in Garibbo and Palucci (2014) for detecting the above issues; among the types of detection, bulk detection and trace detection are used, whereas for modes, point detection, stand-off detection, and distributed detection are generally used.

To retrieve the information about atomic and molecular energy, molecular geometry, chemical bonds, spectroscopic techniques, or terahertz techniques are used. Spectroscopic technique includes laser photoacoustics (PA) spectroscopy, laser-induced breakdown spectroscopy, laser Raman spectroscopy, and light detection and ranging (LIDAR), which is preferably used to trace the explosive precursors and compounds. Photonics is used for the detection of explosives, biological warfare agents (BWAs), chemical warfare agents (CWAs), and drugs.

The principle of LIDAR is same as the principle of RADAR where a light of short pulse is directed toward the target and then backscattered radiation is analyzed. In the analysis, the time gap between the transmission and reception of light pulse determines the distance, and the intensity of light along with the spectral distribution yields the optical property of target and medium. Elastic scatter LIDAR is typically used to study the aerosol and cloud, whereas Raman scattering LIDAR (inelastic) is used to determine the specific gas content. Differential absorption LIDAR (DIAL) is mostly used to determine the gas such as CO₂, O₃, SO₂, NO, NO₂, Hg, and H₂O in atmospherics by transmitting two laser beams of two wavelengths. Wind speed is measured by Doppler LIDAR by considering the frequency shift. LIDAR application can also be extended toward for the monitoring of temperature, density, and pressure in all-weather conditions. Also, using remote sensing technique, LIDAR is used to measure the physical and chemical properties of a targeted area mostly in forest. Airborne LIDAR is also used for the measurement at some area in the case of volcanic plume emission, and space-borne LIDAR can also be used for atmospheric measurement in space technology experiment.

Eriksrud and Kringlebotn (2014) suggested recently the fiber optic sensor technologies, which are used in oil and gas sector as permanent sensor in offshore wells where hydrocarbon is produced. It is reported in 1991 that the first temperature and pressure gauge system based on optical technology is installed in the above-said fields. The two main technologies such as FBG and Raman scattering are dominating in this field. The main advantages of optical sensor over electrical sensor are its ability to withstand higher temperature over a long period and also it has no active components.

Raman and fluorescence spectroscopy are universally used in biospectroscopy for forensic application discussed by Tajani (2014). Comparably, Raman spectroscopy is mostly used

over fluorescence type to examine all types of body fluid and dry traces because of its high selectivity and peculiarity to biochemical species.

15.3.1 Photonics for Biomedical Application

A 3D PC optical sensor of background material poly dimethylsiloxane (PDMS) and nanoparticles is discussed (Endo et al. 2007) for environmental monitoring to detect the volatile organic compound. Different photonic sensing for the defense and security applications and their future capabilities is reviewed (Leheny and McCants 2008). An accurate measurement for the concentration of sugar, sodium chloride, and alcohol based on the variation of PBG of a square lattice photonic structure is proposed (Palai and Tripathy 2012). The whole system is simulated using the PWE method. A PC ring resonator (PCRR) is proposed by Robinson and Nakkeeran (2012) to measure the salinity of sea water over the temperature range of 0°C–25°C. The output of sensor is changed in accordance with the refractive index of sea water as it has a distinctive refractive index for different concentrations of salt level.

Different photonic sensors with their utility, simulation, and design are widely discussed (Passaro et al. 2012). Specifically, the compatibility of photonic sensors with CMOS technology is focused. In the whole review process, several applications of photonic sensors such as food processing, biomedical, automotive, medicine, aerospace with their materials, architecture, sensing principle, and technology are the main discussion. The PWE simulation method using PBG variation of different parameters of biomedical field is measured (Palai et al. 2012, 2014). In the above works, Cygel strength and sucrose concentration in hydrogel are measured, respectively, using a 2D square lattice and silicon as a background material. However, the concentration of glycerol in B-H-G solution is measured using 3D PCS using the same PWE method where PBG is varied linearly with the concentration of Cygel (Palai and Tripathy 2014).

Instead of PCS, PCF is used to measure the concentration of potassium chloride (Palai et al. 2013). Here, silicon is taken as a background material having circular air holes of 400 nm and a lattice constant of 1 μm with a defect at the center. FDTD method is used (Muduli et al. 2013) to investigate the different optical properties such as dispersion loss, confinement loss, effective mode area, and index of a chalcogenide hexagonal PCF. At the wavelength of 633 and 1500 nm, the measurement of impurity concentration in chalcogenide glass is proposed (Palai 2014a). To get the impurities, both reflection and absorption losses are considered by PWE and Maxwell's curl equation, respectively. In this work, the impurity concentration is varied linearly with reflectance, absorbance, and transmittance. This linear variation leads to get the desired impurity concentration.

A polarimetric sensor is developed to monitor the curing process of magnetorheological elastomer (MRE) (Ramakrishnan et al. 2014), which is based on the buffer stripped high birefringent PCF. By this, different stages of curing process are clearly visible from the polarization maintaining PCF. To measure the salinity of water, a PC-based optical sensor is developed (Lavanya et al. 2014). Here, the sensor is designed as a dielectric slab waveguide where water sample acts as cladding and PC channel waveguide as a core. The effective index of slab waveguide is varied with the variation of salinity of water, which is captured for the output.

The 3D PCS is used (Palai and Dhir 2015) to calculate the concentration of oxygenated and deoxygenated hemoglobin in human blood at the wavelength of 589 and 633 nm, respectively. Here the PWE method is used for simulation as well. A new trend of photonic sensor in optical field is reviewed (Frantisek and Jozef 2014) where the current progress

in optical signal processing, fabrication technology, and material technology is discussed. A new type of sensing application using PECVDSiO₂:N/SiO₂ slab waveguide grating (SWG) at 1550 nm is proposed (Jozef et al. 2014) where the fundamental parameters of reflected spectrum are investigated as a function of temperature, cover refractive index, and strain by grating mode R-Soft design tools suite.

The early detection of cancerous cell with the help of dielectric constant is proposed (Sharan et al. 2014). Although the variation between the cancerous cell and the normal cell is very minimum, but still it can be detected by the help of PBG variation in this work. Here, 2D square lattice PC material is used with a line defect, and MIT electromagnetic equation propagation (MEEP) and MIT photonic band (MPB) simulation tools are used to investigate the whole system. MEEP is developed by MIT, which is a free FDTD simulation software package, whereas MPB is the frequency domain analysis tool and both are used to get the details of inner attributes during simulation.

Using similar type of square lattice, the concentration of potassium chloride is investigated in their aqueous solution (Palai 2014b). Here the square lattice is a silicon material with 8×8 air holes. However, in this case, the concentration of potassium chloride is varied logarithmically with the variation of PBG when simulated by PWE method. A monolithic crystalline silicon membrane based on the PC is proposed to develop a pressure sensor with different compliances (Wu et al. 2015). In this, the different figures of merits are also discussed. The PC sensor is also compared with the oxide diaphragm and found better sensitivity. A PC cavity sensor on SiO platform is discussed with its design, fabrication, and characterization, which is of high quality factor (Q) and high sensitivity (Zhang et al. 2015). The high sensitivity is achieved by optimizing the structure of cavity.

An automatic system for the detection of cervical cancer, which is based on the PC biosensor, is proposed (Nithin et al. 2015). Here, the dielectric constant is changed from a normal to a cancer-affected tissue very sensitively when influenced by electromagnetic radiation that ranges from UV to IR. The frequency and amplitude spectrum of the output reveals a distinct signature when a slight change in refractive index in the cervical tissue took place. Machine learning technique is also used to distinguish between the normal and the cancer-affected tissue. MEEP is used for the simulation of sensor, which is an open-source software worked under Linux operating system developed by MIT. A graphical user interface (GUI) application is also developed for easy classification between two types of cells. In this, a wavelength shift of 0.0392 and an amplitude shift of 0.0202 occurred from normal to cancerous tissue. The same method is proposed to detect *Salmonella typhi* (an agent responsible for typhoid fever; Kerimani et al. 2015; Nithin et al. 2015). From the band structure, it is found that a reasonable shift in frequency and amplitude is occurred with a slight change in refractive index. Hence, this work exhibits a much better quality factor of 85,530 with the sensitivity of 1 nm/RIU. The IMECIPKISS tool is used to design the layout and for the generation of GDSII file and ASCII code OWL VISION tool is used. The detection of antibodies using solid core photonic crystal fiber (SC-PCF) is proposed in the range of 1300–1700 nm. It also described a label-free monoclonal antibody (mAb) sensor using the absorption spectroscopy.

15.3.2 Embedded System Using Arduino for Biomedical Application

Phonocardiogram (PCG) signal simulator is developed based on Arduino, which generates the graphical representation of both normal and defective human heart (Mohamed 2017). Discrete wavelet transform is used for preprocessing of heart sound datasets to represent the different scenarios of heart sound for clinical identification. The work is

very much beneficial to the field of physiological signal analysis. A secured surveillance system for reading and storing patients' information using IoT application, which is useful for healthcare application (Jayapradha et al. 2017). Lot of sensors are used to get the relevant information about the patient activity and transmitted using a very low power to local and cloud server. Arduino UNO is used as a chief IoT device along with the associated. A smart chair (telemedicine-based health monitoring system) is designed to monitor the physiological parameters of human body by the help of sensors when the subject is on the chair. The signals generated from the human body are transmitted through the sensors attached and then processed by Arduino development board to analyze any abnormalities. The resulting signals are then transmitted through the Wi-Fi module to a web server for further processing and storage for future use. Sethy and Pahuja (2017) presented a system, which can record real-time heart rate using Arduino platform as hardware for detection of arrhythmia. The software deals with statistical mathematical model to receive the real-time data for detection of any abnormality in human heart. Winderbank-Scott and Barnaghi (2017) described a wireless monitoring system for pediatric environment, which consists of Arduino-based sensor system along with the Android app for processing of different biomedical sensor signals. An Arduino-based voice-controlled wheelchair was developed for physically challenged person to control the movement, which is also equipped with obstacle detection system and Global System for Mobile communications (GSM)-based navigation for safety (Raiyan et al. 2017). Arduino Mega series of microcontroller along with Easy VR3 speech recognition module are the main components of the wheelchair.

15.4 Results and Discussion

Basically, this chapter deals with a case study where the entire calculation is computed. Further, a complete information with respect to polyacrylamide (PAM) hydrogel with sucrose solution is disclosed. Finally, the outcomes of different biomedical chemicals have been revealed.

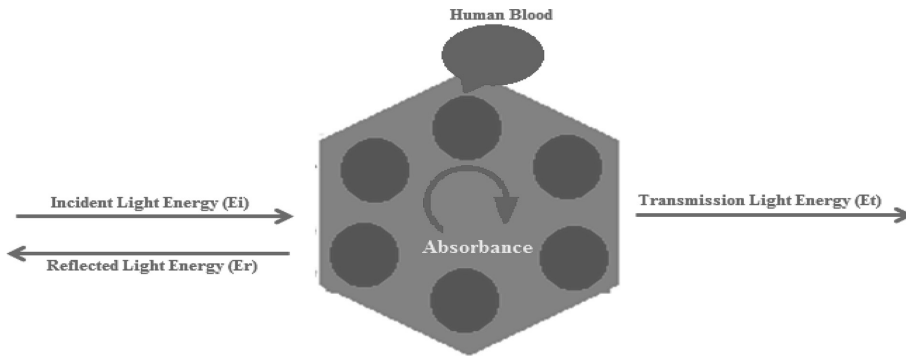
15.4.1 Computational Analysis of 2D PCS with Human Blood: A Case Study

Considering the study by Swain and Palai (2016), a honeycomb lattice structure is taken as a particular case to calculate the transmitted light energy when human blood containing different concentrations of hemoglobin infiltrates in the air hole as shown in [Figure 15.3](#).

When the light of wavelength 589 nm is passed through the honeycomb structure, a part of light energy is reflected back, some part of the energy is getting absorbed in the structure itself, and the rest part of the light is passed through the structure. Here, reflected energy depends on the width of the PBG of the material, and the absorbance energy is depended on the material used for the substrate and infiltration (human blood containing different concentrations of hemoglobin).

Considering a simple mathematics for reflected and absorbance energy, the transmitted light energy is calculated by the following:

$$E_t = (E_i - E_r)e^{-(\alpha t + \beta d)} \quad (15.21)$$

**FIGURE 15.3**

Process of calculating the transmission light energy using a honeycomb structure by measuring the hemoglobin concentration in human blood.

where E_t = transmitted light energy, E_i = incident light energy, E_r = reflected light energy, and $e^{-(\alpha t + \beta d)}$ is an absorption factor related to the absorption coefficient.

Furthermore, a generalized expression, which co-relates between energy and wavelength, is given by the following:

$$E_r = \frac{1.24}{\lambda_r(\mu\text{m})}, \quad (15.22)$$

where λ_r = wavelength of reflected light, which can be obtained from the dispersion diagram of PWE simulation. Dispersion diagram is a graph resulted from the PWE simulation, which gives the information about the PBG whose width is varied depending upon the different concentrations of hemoglobin to be measured present in human blood. This graph is plotted by taking the normalized frequency in x -axis and wave vector in y -axis as shown in [Figure 15.4](#).

In [Figure 15.4](#), bold line represents the width of PBG, where the transmission of light is completely forbidden. The width represents the reflected energy, which depends on several factors such as lattice spacing, diameter of air holes, refractive index of structure, and human blood—both. Reviewing [Figure 15.4](#), which is the dispersion diagram for 120 g/L concentration of deoxygenated hemoglobin in human blood at $\lambda = 589$ nm, the width of the PBG can be measured by considering the normalized frequency (a/λ).

To convert this into normalized frequency in electron volts, Equation (15.3) is applied as follows:

$$E_r = \frac{1.24}{a} \times \frac{a}{\lambda} \quad (15.23)$$

$$E_r = 1.24 \times \frac{a}{\lambda} \quad (15.24)$$

where “ a ” represents the lattice spacing and taken as $1 \mu\text{m}$.

The following table shows the lists of reflected light energy for each concentration, which plays important role for getting the transmitted light energy ([Table 15.1](#)):

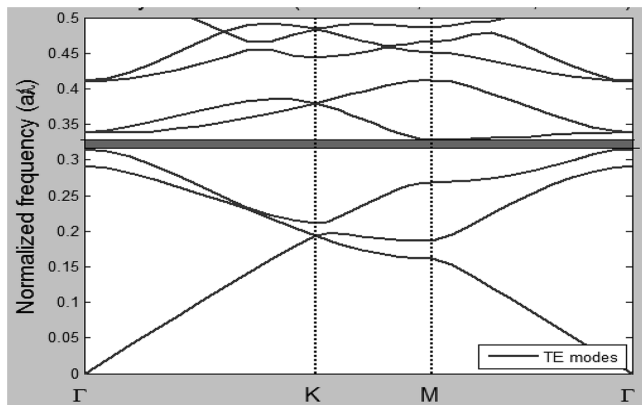


FIGURE 15.4
Dispersion diagram for 120 g/L concentration of deoxygenated hemoglobin in human blood. (From Swain, K.P. and Palai, G., *Optik*, 127, 3333–3336, 2016.)

TABLE 15.1

List of Reflected Light Energy for Different Concentrations of Hemoglobin

Concentration (g/L) of Hemoglobin in Blood	$\lambda = 589 \text{ nm}$	Bottom of the Upper Layer	Top of the Lower Layer	Width of PBG	Energy of Reflected Energy $E_r = \text{Width of PBG} \times 1.24$
0	1.335	0.3297	0.3159	0.0138	0.017112
20	1.339	0.3295	0.3158	0.0137	0.016988
40	1.342	0.3293	0.3157	0.0136	0.016864
60	1.345	0.3292	0.3157	0.0135	0.01674
80	1.348	0.329	0.3156	0.0134	0.016616
100	1.35	0.3289	0.3156	0.0133	0.016492
120	1.353	0.3287	0.3155	0.0132	0.016368

Moreover, the computation for absorption loss pertaining to the above-said photonic structure is made as follows:

Here, absorption loss is occurred due to two factors: one for the material used as a background in the honeycomb lattice and other is due to the human blood containing the hemoglobin concentration.

Absorption Loss Due to the Background Material

It is expressed as $e^{-\alpha t}$, where α = absorption coefficient for the background material and t is the thickness of the material. In this particular reference, GaAs is used as a background material whose absorption coefficient (α) = 51082.7643 and $t = 3 \times 10^{-4} \text{ cm}$. After multiplying, we obtain the following:

$$\alpha t = 15.32483 \text{ and } e^{-\alpha t} = 0.00000022. \quad (15.25)$$

It is noted that this loss is fixed for all concentrations of hemoglobin as a background material is same for all the simulations.

Absorption Loss Due to the Hemoglobin in Human Blood

It is expressed as $e^{-\beta d}$, where $\beta = \epsilon c$ = absorption coefficient and ϵ = extinction coefficient of blood, d is the diameter of air holes, and “ c ” is the concentration of hemoglobin in human blood.

Again, in this reference, $d = 3 \times 10^{-4}$ cm and $\epsilon = 17082$. So finding the value for ϵd by reference (Swain and Palai 2016, Tabulated Molar Extinction Coefficient)

$$\epsilon d = \left[\{2.303 \times 17082\} / 64500 \right] 0.0003 = 0.0001829 \quad (15.26)$$

Table shows the values of $e^{\alpha t}$ and $e^{-\beta d}$ related to different concentrations of hemoglobin (Table 15.2).

Applying all the parameters, the transmitted light energy through the structure is calculated using Equation (15.1), and the following table provides the value transmitted energy (in electron volts) for different concentrations of hemoglobin in human blood (Table 15.3).

15.4.1.1 Arduino Interfacing with Proteus Simulation

In the whole process of PWE simulation carried out by MATLAB, whatever voltages generated at the output (mentioned in the table) are made available at the COM port of the PC. This is performed by writing a small program using serial communication library function of MATLAB. Also, Arduino board is having an in-built communication (UART-Universal asynchronous receiver transmitter) facility, which can be used to transfer the data from COM port to its UART by keeping the baud rate as 9600 for both transmitter (COM port) and UART of Arduino. This is possible by establishing a bridge by activating the serial port in MATLAB. Then data are fetched from COM port to Arduino for displaying the output corresponding to different concentrations through LCD. The above process is again simulated by proteus ISIS simulation to show the details of output along with the structure details (Figures 15.5 and 15.6).

TABLE 15.2

List of Absorbance Light Energy for Different Concentrations of Hemoglobin

Concentration of Hemoglobin “C” in g/L	Absorbance Energy				
	Due to Hemoglobin			Due to Structure	Total Absorbance Energy
	ϵd	$\epsilon d c$	$e^{-\beta d} = e^{-\epsilon c d}$	$e^{-\alpha t}$	$A = e^{-\alpha t} \times e^{-\beta d}$
0	0.00018	0	1.0000000000	0.00000022	0.0000002210
20	0.00018	0.003658	0.99963427	0.00000022	0.0000002209
40	0.00018	0.007316	0.9992686700	0.00000022	0.0000002208
60	0.00018	0.010974	0.9989032000	0.00000022	0.0000002208
80	0.00018	0.014632	0.9985378700	0.00000022	0.0000002207
100	0.00018	0.01829	0.9981726700	0.00000022	0.0000002206
120	0.00018	0.021948	0.9978076100	0.00000022	0.0000002205

TABLE 15.3

List of Transmission Light Energy Emerging Out from the Photonic Structure for Different Concentrations of Hemoglobin

Conc. of Hemoglobin (g/L)	E_r (eV) = Difference $\times 1.24$	E_i (eV)	$E_i - E_r$	Absorbance (A) = $e^{-\alpha t} \times e^{-\beta d}$	E_t (eV) = $(E_i - E_r) \times A$
0	0.017112	2.1	2.082888	0.0000002211	0.0000004604
20	0.016988	2.1	2.083012	0.0000002210	0.0000004603
40	0.016864	2.1	2.083136	0.0000002209	0.0000004602
60	0.01674	2.1	2.08326	0.0000002208	0.0000004600
80	0.016616	2.1	2.083384	0.0000002207	0.0000004599
100	0.016492	2.1	2.083508	0.0000002207	0.0000004597
120	0.016368	2.1	2.083632	0.0000002206	0.0000004596

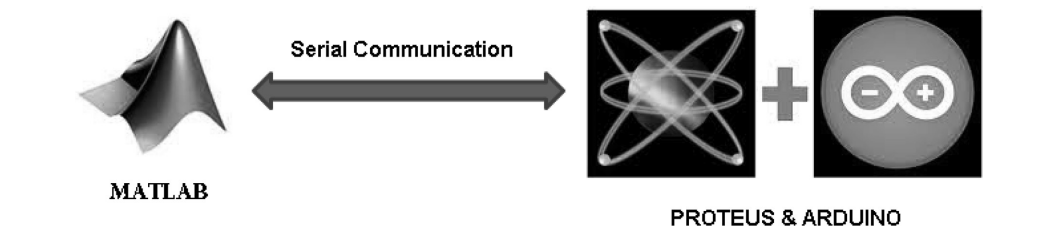


FIGURE 15.5 Interfacing of Arduino and Proteus with Matlab through serial communication.

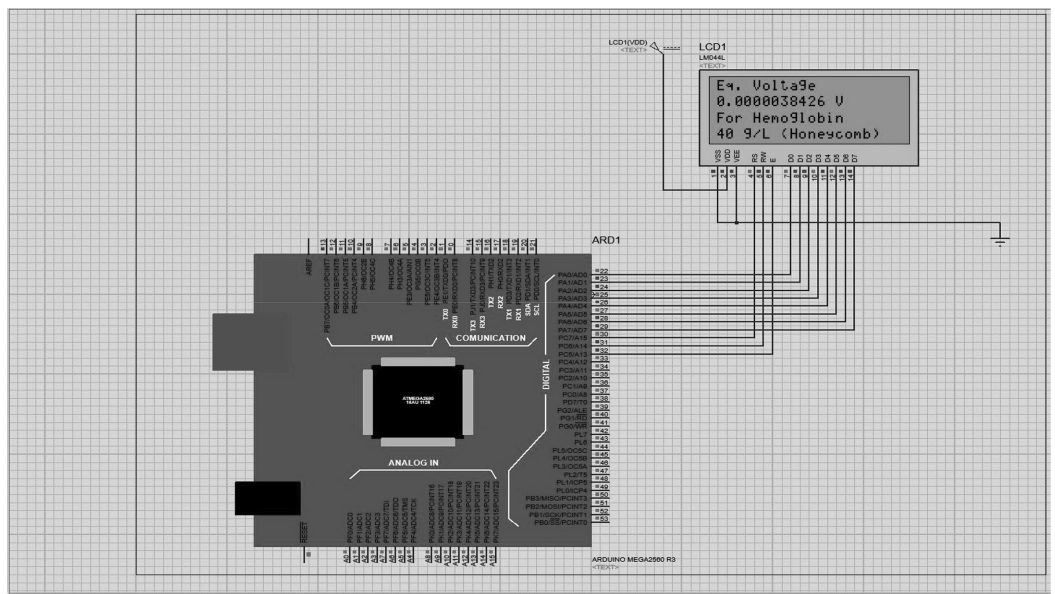


FIGURE 15.6 Proteus simulation showing the output voltage on LCD.

15.4.2 Complete Biomedical Investigation for PAM Hydrogel Solution

As the name implies, hydrogel, a polymeric material, can absorb lot of water. It is highly used in biomedical applications such as wound dressing, drug encapsulation, drug delivery, and cosmetic surgery. It has many advantages such as permeable, lubricious, hydrophilic, and environmentally sensitive and also has some disadvantages such as poor mechanical property, hard to handle, and sterilization. PAM is a type of hydrogel mostly used to make soft contact lenses.

Sucrose (table sugar) is made from sugarcane known for its harmful application to mankind such as fluctuation in blood sugar level frequently, which affects the human mood significantly resulting in many health problems such as irritation, fatigue, dental decay, and diabetics. However, when it is added with PAM hydrogel, the optical clarity is enhanced.

Palai et al. (2014) discussed to measure the sucrose concentration in PAM hydrogel solution using a two dimensional square photonic lattice. In this, silicon material is used as a substrate with a lattice constant of $1\ \mu\text{m}$ and an air hole radius of $0.4\ \mu\text{m}$. When hydrogel solution containing different concentrations of sucrose is infiltrated to the air holes of the photonic structure, then by the linear variation of PBG, the output light energy (in electron volts) is calculated. By examining the value of the light energy, different concentrations of sucrose are calculated.

In this work, instead of using silicon as a substrate material, AlGaAs is used as background material, which satisfies all the nonlinear figure of merits. Here all of two-dimensional photonic structures such as square, triangular, and honeycomb along with the three-dimensional structures are investigated to measure the output light energy, which directly depend on the PBG of the material. In all the cases, PWE simulation is used to get the dispersion diagram where the width of the PBG can be calculated, which decides the amount of light energy emerging out from the substrate (Figure 15.7).

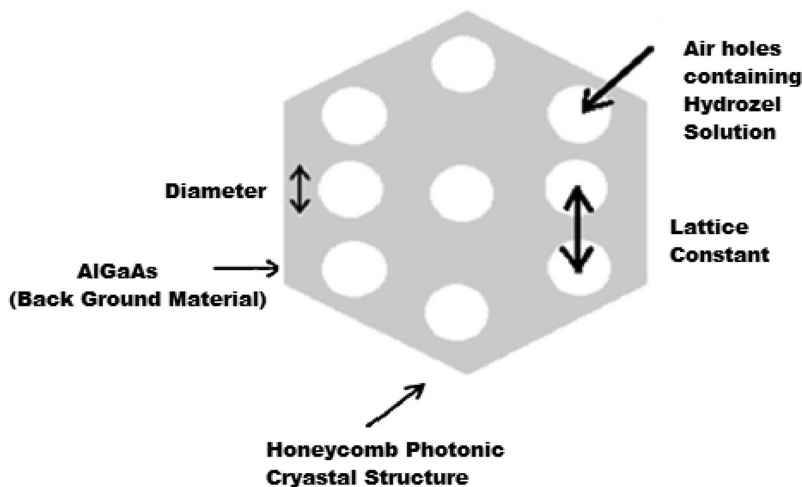


FIGURE 15.7
Honeycomb structure using AlGaAs as a background material.

15.4.2.1 Honeycomb Structure

A honeycomb structure is proposed in this work, which is made from AlGaAs substrate having nine air holes of radius 420 nm and a spacing between two adjacent holes of 1 μm . When a light source of wavelength 589 nm is incident on the structure, which already contains the hydrogel solution, then according to the width of PBG, some light is reflected back, some light is absorbed by both the structure and the hydrogel solution, and the rest of the light is passed through the structure. The light, which is passed through the structure, plays an important role for the entire calculation. The entire investigation is accomplished by the following steps.

Step-1

According to the dielectric constant of all corresponding sucrose concentration per the table given, the dispersion diagram is determined. In [Figure 15.8](#) of dispersion graph (a to c), red portions show the width of the PBG created for the different concentrations of sucrose (0%, 10%, 20%, 30%, 40%, and 120%) in hydrogel solution. In the dispersion diagram, x -axis shows the normalized frequency (a/λ), whereas y -axis points to wave vector (in m^{-1}) ([Table 15.4](#)).

Step-2

The width of the PBG variation is determined by calculating the difference between the corresponding top and bottom of forbidden bandgap in each dispersion diagram ([Table 15.5](#)).

Step-3

By taking into account the width of PBG and applying the Equation (15.11) in [Section 15.4.1](#), the output energy is calculated using the following setup. In this, the light coming out from the photonic structure is incident on the photodetector, which converts the light energy to electrical energy. Then the output is displayed on an LCD through a microcontroller using Arduino board. Here, those energy coming out from the structure is expressed in electron volts (eV), but output is taken at the Arduino as volt ([Figure 15.9](#)).

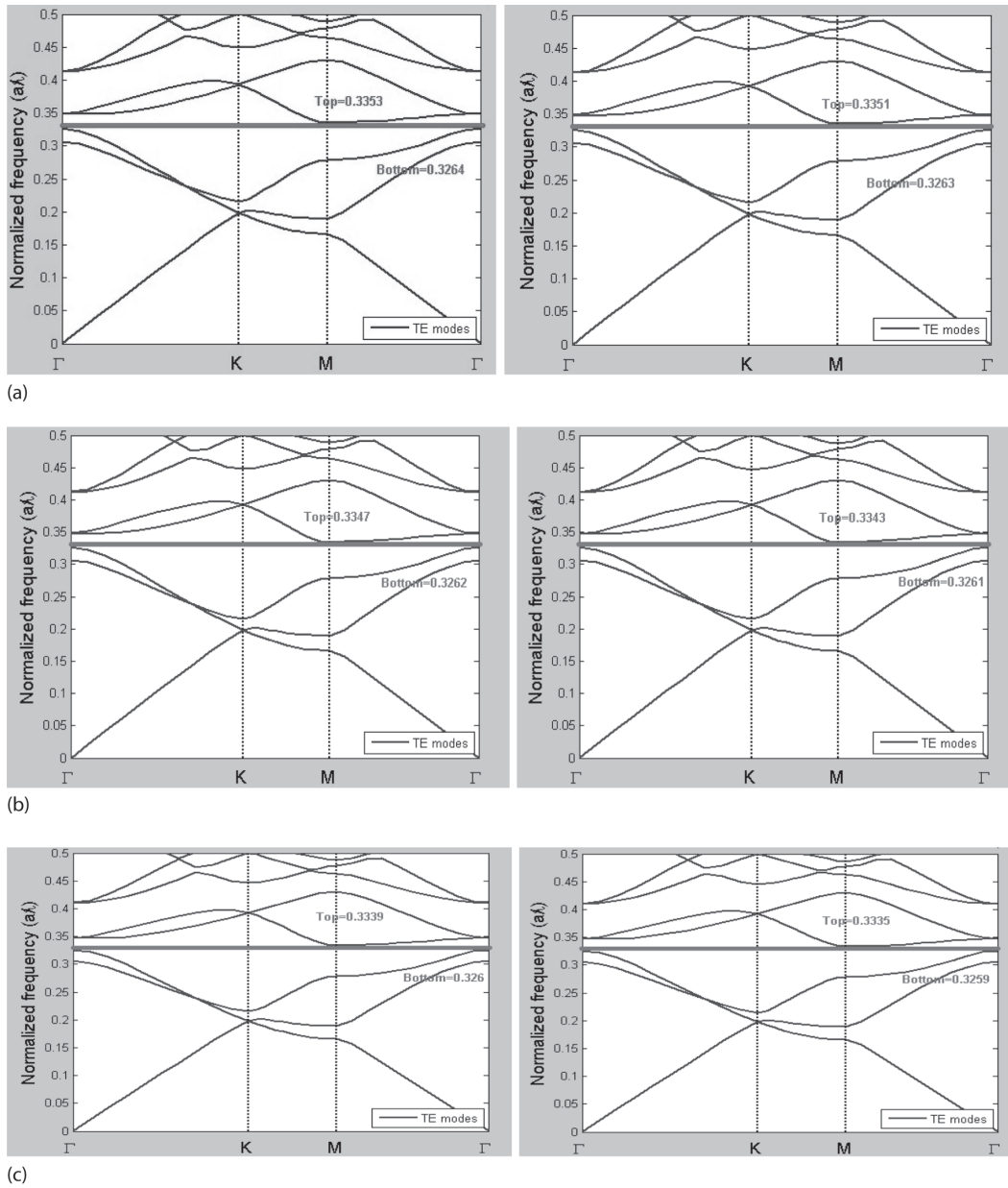
It is noted that the energy absorbed by the hydrogel solution is very negligible. So, the entire calculation is done by omitting the absorbance energy due to the hydrogel solution ($e^{-\beta d}$). The following table shows the output energy corresponding to each percentage of concentration of sucrose, which is explained in [Section 15.4.1](#) in detail ([Table 15.6](#)).

15.4.2.2 Triangular Lattice

A triangular photonic structure having AlGaAs as a background material is considered, which contains six numbers of air holes where hydrogel solution is to be infiltrated. Here diameter of air holes is taken as 800 nm and a lattice constant as 1 μm . Following the same steps as discussed in honeycomb structure, first the dispersion diagram is plotted as shown in [Figures 15.10](#) and [15.11a–c](#).

The following table shows the width of PBG corresponding to each concentration of sucrose in hydrogel solution for a triangular structure ([Table 15.7](#)).

Per the calculation performed in honeycomb structure, the output energy is calculated similarly for the different concentrations of sucrose in the hydrogel solution ([Table 15.8](#)).

**FIGURE 15.8**

(a) Dispersion graphs for 0% and 10% concentrations. (b) Dispersion graphs for 20% and 30% concentrations. (c) Dispersion graphs for 40% and 50% concentrations.

15.4.2.3 Square Lattice

A 2D square photonic structure having air holes of diameter 800 nm is shown in [Figure 15.12](#). PWE simulation is carried out when the light energy of wavelength 589 nm is incident on this structure and the hydrogel solution is infiltrated on the air holes to measure the output light energy, the following dispersion diagram is plotted ([Figure 15.13](#)).

TABLE 15.4

Dielectric Constant of PAM-Hydrogel Sucrose Concentration

% of Sucrose Concentration	Dielectric Constant (ea) of PAM Hydrogel Sucrose Solution
0	1.93
10	1.94
20	1.96
30	1.98
40	2.00
50	2.02

TABLE 15.5

The PBG Width for Different Concentrations of Sucrose in Hydrogel Solution

Honeycomb Structure Using AlGaAs			
Sucrose	Bottom	Top	Width of PBG
0	0.3353	0.3264	0.0089
10	0.3351	0.3263	0.0088
20	0.3347	0.3262	0.0085
30	0.3343	0.3261	0.0082
40	0.3339	0.326	0.0079
50	0.3335	0.3259	0.0076

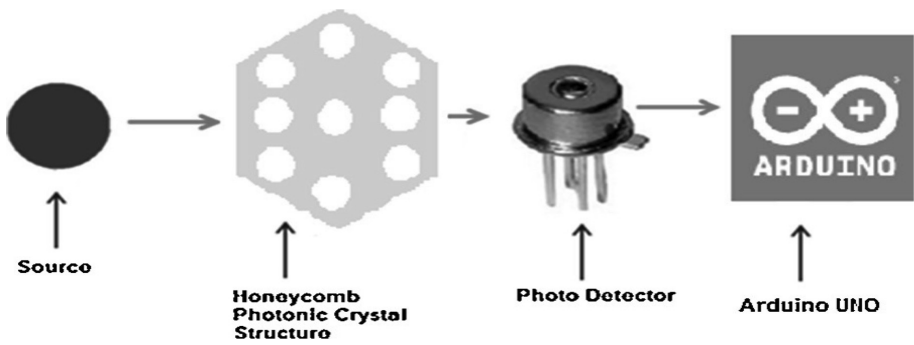


FIGURE 15.9
Experimental setup to measure the transmission output through the structure.

After getting the dispersion diagram, the width of the PBG is calculated, and the output of transmitted light (in volt) is also calculated for different concentrations of sucrose in the hydrogel solution (Tables 15.9 and 15.10).

15.4.2.4 3D Lattice

Figure 15.14 shows the 3D photonic structure having the lattice constant of 1 μm and the diameter of air holes of 432 nm. Similar to the previous case, the following dispersion

TABLE 15.6
List of the Output (Volt) for Each Concentration of Sucrose (in %)

Sucrose	Width of PBG	Output in Volt
0	0.0089	0.00000039482163
10	0.0088	0.00000039484506
20	0.0085	0.00000039491537
30	0.0082	0.00000039498568
40	0.0079	0.00000039505599
50	0.0076	0.00000039512630

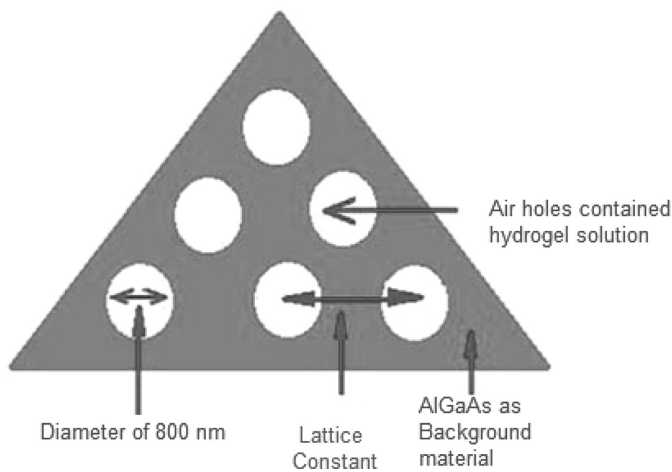
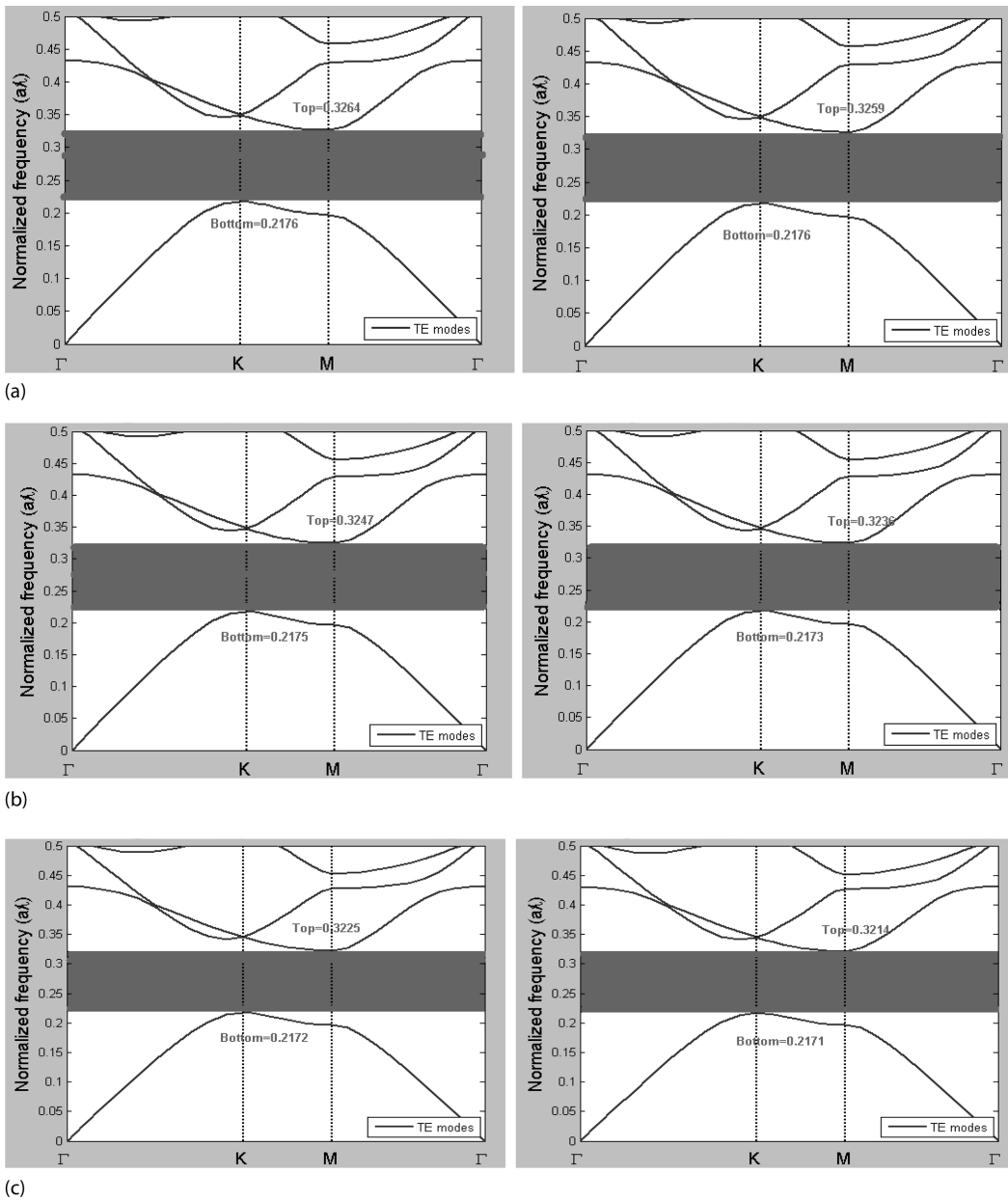


FIGURE 15.10
Triangular photonic structure using AlGaAs as a background material. (From Swain, K.P. et al., Realization of accurate urine-glucose sensor using triangular photonic crystal structure. *2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES)*, IEEE, 1021–1024, 2016.)

diagrams are obtained for different concentrations of sucrose in hydrogel solution (Figure 15.15, Tables 15.11 and 15.12).

Summarizing all the structures, the width of the PBG and their corresponding output voltage is tabulated as follows. By analyzing the graph, it is clear that the square and triangular structure of photonic structure is best suited to measure the sucrose concentration in hydrogel solution having $R^2 = 99.3$. It is also interesting that the width of PBG is varied reversely with the output equivalent voltage of the transmitted light energy. In the entire investigation, the absorption due to hydrogel solution is ignored as it has very little impact on the calculation, but the absorption due to the background material (AlGaAs) is constant (Figures 15.16 and 15.17, Tables 15.13 and 15.14).

Again, the simulation is performed using proteus ISIS simulation package to display the output on the LCD through Arduino UNO board as shown in the figure. The output is shown on LCD for “0%” and “50%” concentration of sucrose in the hydrogel solution (Figures 15.18 and 15.19).

**FIGURE 15.11**

(a) Dispersion graphs for 0% and 10% sucrose concentrations in hydrogel solution. (b) Dispersion graphs for 20% and 30% sucrose concentrations in hydrogel solution. (c) Dispersion graphs for 40% and 50% sucrose concentrations in hydrogel solution.

TABLE 15.7
The Width of PBG for Different Concentrations of Sucrose in Hydrogel Solution

Triangular Structure			
Sucrose	Bottom	Top	Width of PBG
0	0.3264	0.2176	0.1088
10	0.3259	0.2176	0.1083
20	0.3247	0.2175	0.1072
30	0.3236	0.2173	0.1063
40	0.3225	0.2172	0.1053
50	0.3214	0.2171	0.1043

TABLE 15.8
List of Output (Volt) for Each Concentration of Sucrose (%)

Triangular Structure		
Sucrose	Width of PBG	Output in Volt
0	0.1088	0.0000003714
10	0.1083	0.0000003715
20	0.1072	0.0000003718
30	0.1063	0.0000003720
40	0.1053	0.0000003722
50	0.1043	0.0000003725

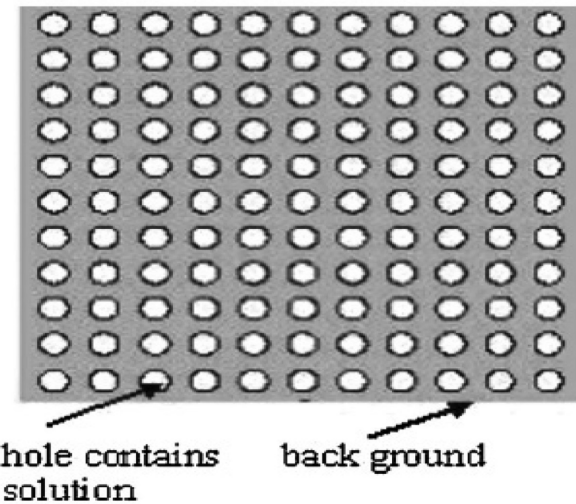
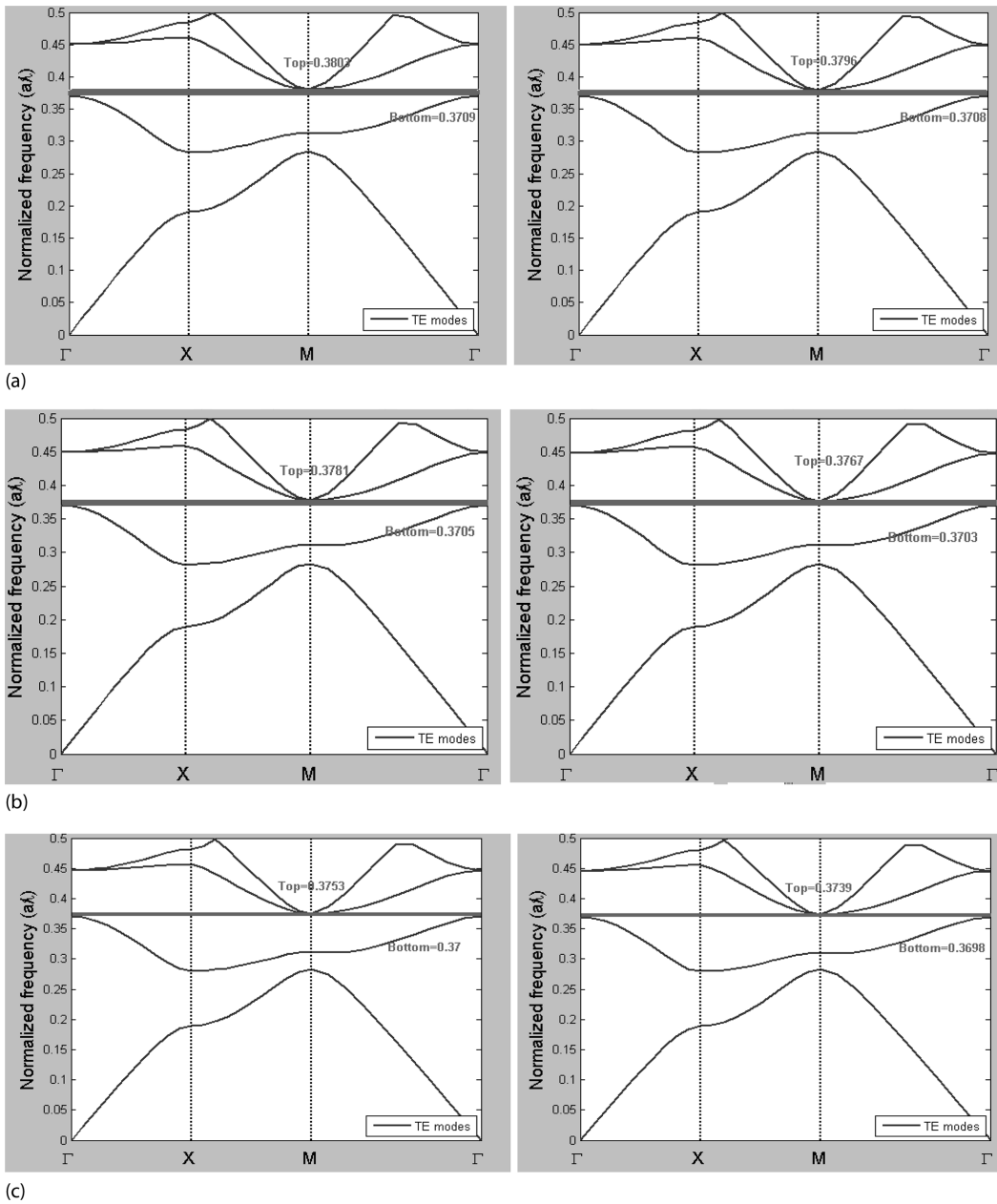


FIGURE 15.12
Square photonic crystal structure using AlGaAs as a background material. (From Palai, G. et al., *Optik*, 125, 349–352, 2014.)

**FIGURE 15.13**

(a) Dispersion graphs for 0% and 10% concentrations. (b) Dispersion graphs for 20% and 30% concentrations. (c) Dispersion graphs for 40% and 50% concentrations.

TABLE 15.9
The PBG Width for Different Concentrations of Sucrose in Hydrogel Solution

Square Structure			
Sucrose	Bottom	Top	Difference
0	0.3803	0.3709	0.0094
10	0.3796	0.3708	0.0088
20	0.3781	0.3705	0.0076
30	0.3767	0.3703	0.0064
40	0.3753	0.37	0.0053
50	0.3739	0.3698	0.0041

TABLE 15.10
List of Output (Volt) for Each Concentration of Sucrose (%) in Square Structure

Square Structure		
Sucrose	Difference	Output in Volt
0	0.0094	0.0000003947
10	0.0088	0.0000003948
20	0.0076	0.0000003951
30	0.0064	0.0000003954
40	0.0053	0.0000003957
50	0.0041	0.0000003959

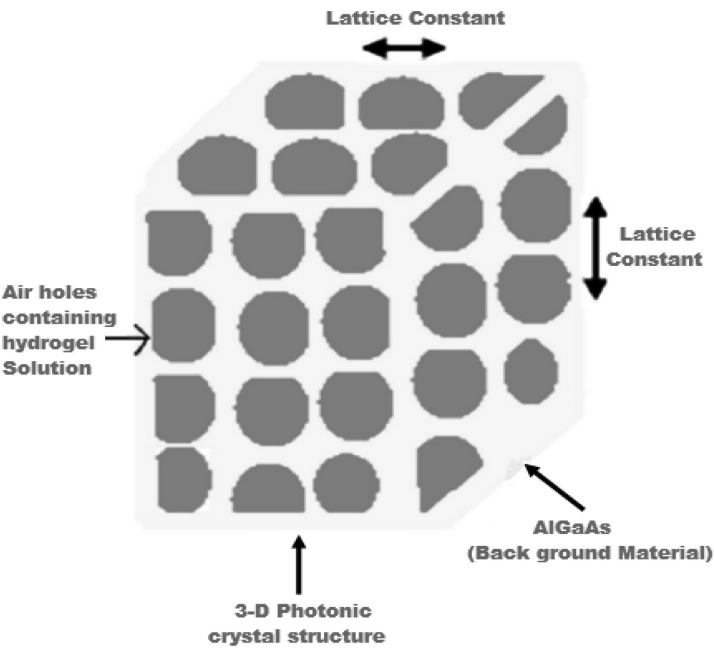
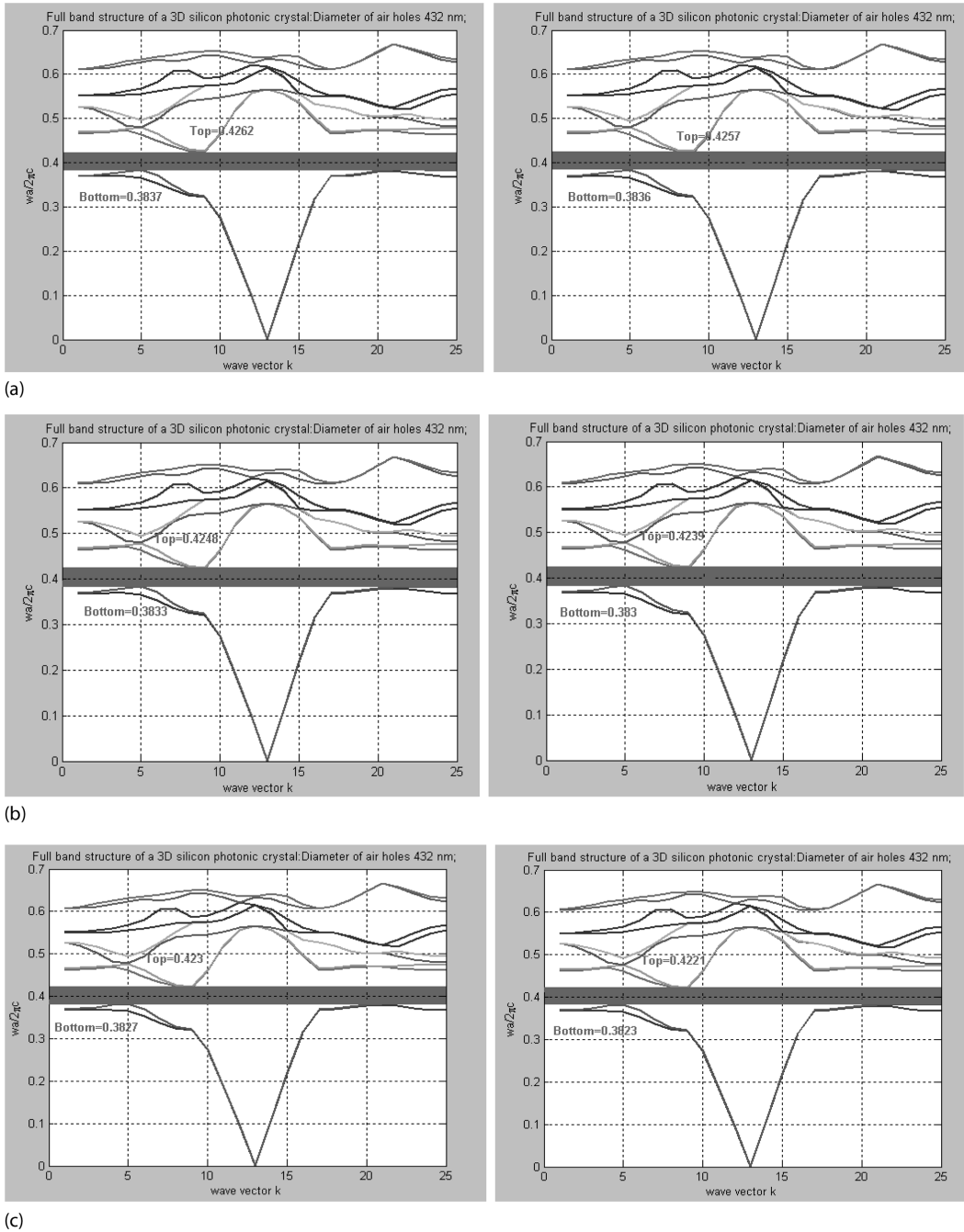


FIGURE 15.14
3D photonic structure using AlGaAs as a background material. (From Palai, G. and Dhir, T.K. *Optik*, 126, 478–482, 2015.)

**FIGURE 15.15**

(a) Dispersion graphs for 0% and 10% concentrations. (b) Dispersion graphs for 20% and 30% concentrations. (c) Dispersion graphs for 40% and 50% concentrations.

TABLE 15.11
The PBG Width for Different Concentrations of Sucrose in Hydrogel Solution

3D Lattice			
Sucrose	Bottom	Top	Difference
0	0.4262	0.3837	0.0425
10	0.4257	0.3836	0.0421
20	0.4248	0.3833	0.0415
30	0.4239	0.383	0.0409
40	0.423	0.3827	0.0403
50	0.4221	0.3823	0.0398

TABLE 15.12
List of Output (Volt) for Each Concentration of Sucrose (%) in 3D Structure

3D Lattice		
Sucrose	Difference	Output in Volt
0	0.0425	0.00000038694698
10	0.0421	0.00000038704073
20	0.0415	0.00000038718135
30	0.0409	0.00000038732197
40	0.0403	0.00000038746258
50	0.0398	0.00000038757977

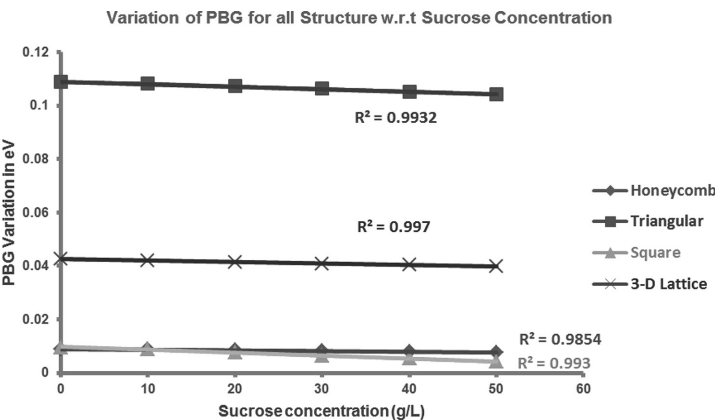


FIGURE 15.16
Graph showing the variations of PBG with respect to sucrose concentration in hydrogel solution for different photonic structures.

15.4.3 Investigation of Other Biomedical Specimens

Hemoglobin:

Hemoglobin concentration is measured using 3D PCS by PWE method for both oxygenated and deoxygenated blood in Palai and Dhira (2015). During simulation absorption loss, both blood and the silicon material are considered. The light

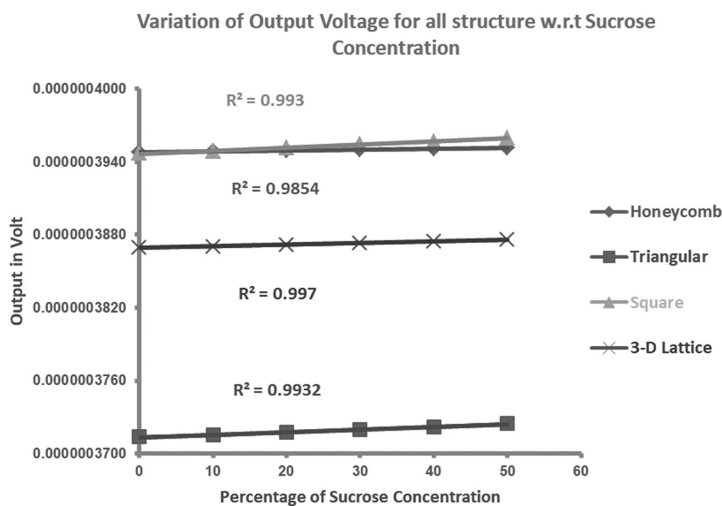


FIGURE 15.17
The variation of output light energy (in volts) with respect to sucrose concentration in hydrogel solution for different photonic structures.

TABLE 15.13
The Variation of PBG Width with respect to Sucrose Concentration in Hydrogel Solution for Different Types of Photonic Structures

Sucrose Concentration (in g/L)	Honeycomb Lattice	Triangular Lattice	Square Lattice	3D Lattice
	Photonic Bandgap (in eV)	Photonic Bandgap (in eV)	Photonic Bandgap (in eV)	Photonic Bandgap (in eV)
0	0.0089	0.1088	0.0094	0.0425
10	0.0088	0.1083	0.0088	0.0421
20	0.0085	0.1072	0.0076	0.0415
30	0.0082	0.1063	0.0064	0.0409
40	0.0079	0.1053	0.0053	0.0403
50	0.0076	0.1043	0.0041	0.0398

TABLE 15.14
The Variation of Transmission Light Energy with respect to Sucrose Concentration in Hydrogel Solution for Different Type of Photonic Structures

Sucrose Concentration (in g/L)	Honeycomb Lattice	Triangular Lattice	Square Lattice	3D Lattice
	Output (in Volt)	Output (in Volt)	Output (in Volt)	Output (in Volt)
0	0.0000003948	0.0000003714	0.0000003947	0.0000003869
10	0.0000003948	0.0000003715	0.0000003948	0.0000003870
20	0.0000003949	0.0000003718	0.0000003951	0.0000003872
30	0.0000003950	0.0000003720	0.0000003954	0.0000003873
40	0.0000003951	0.0000003722	0.0000003957	0.0000003875
50	0.0000003951	0.0000003725	0.0000003959	0.0000003876

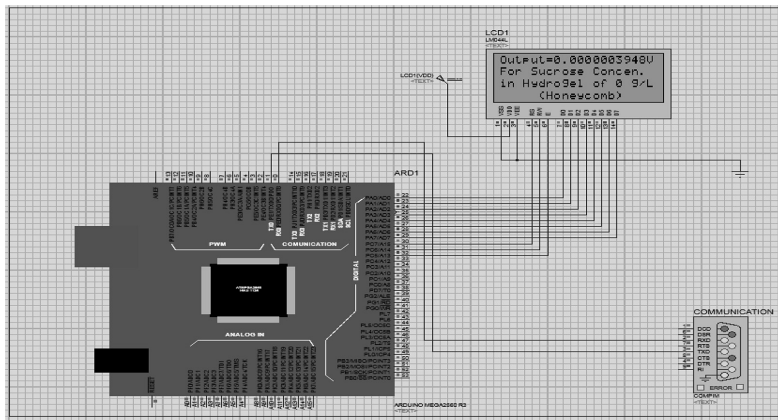


FIGURE 15.18
Proteus simulation to display result for sucrose concentration (0 g/L) in hydrogel solution.

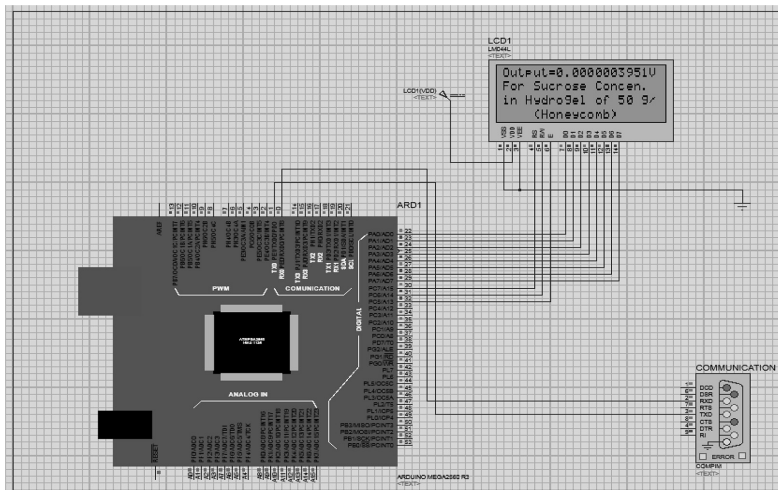


FIGURE 15.19
Proteus simulation to display result for sucrose concentration (50 g/L) in hydrogel solution.

wave of 589 and 633 nm are used for simulation. The 3D crystal structure is realized on a silicon substrate by drilling air holes of diameter 432 nm and spacing of 1 μm . In Swain and Palai (2016), the 2D honeycomb crystal structure is used to calculate the hemoglobin concentration in human blood with more accuracy with respect to other previous works. Here, also same PWE method is used to observe the variation of PBG as previously, but the background material is taken as gallium arsenide (GaAs). The GaAs honeycomb structure is having nine holes of diameter 420 nm and spacing of 1 μm . When a light intensity of 589 nm is fell on the holes of the substrate containing blood concentration, the light energy emitted out from substrate is varied according to the concentration of hemoglobin. Finally, a microcontroller-based system similar to Arduino Uno is used to display the final result on the LCD. In this, both the oxygenated and deoxygenated blood are taken into account.

In this work, hemoglobin is measured in human blood using AlGaSb as a background material for different types of photonic structure with the absorption coefficient $\alpha = 44,005 \text{ cm}^{-1}$. For honeycomb structure, the diameter of air holes is taken as 420 nm, and in square as well as triangular photonic structure, the diameter of air holes is taken as 800 nm. As in [Section 15.4.2](#), the details of the PBG variation and output energy variation with respect to hemoglobin concentration in human blood are shown in [Figures 15.20 and 15.21](#), respectively. By

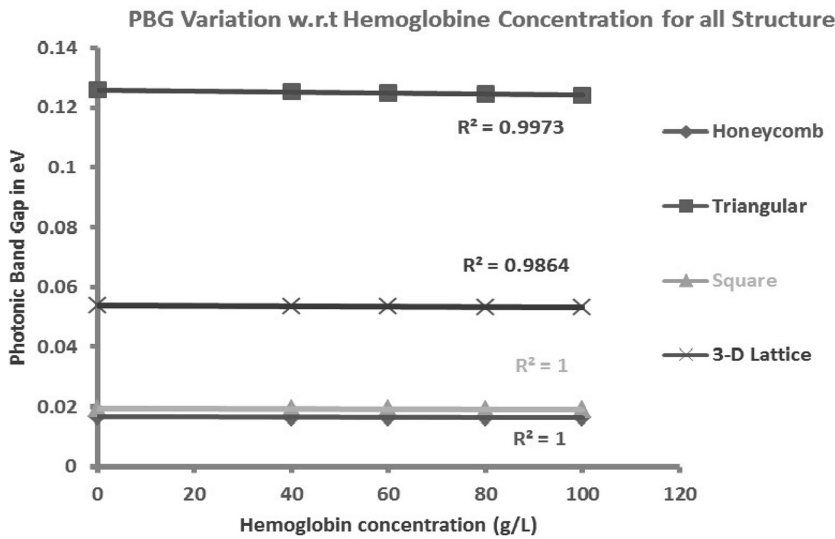


FIGURE 15.20

The variation of PBG with respect to hemoglobin concentration in human blood for different photonic structures.

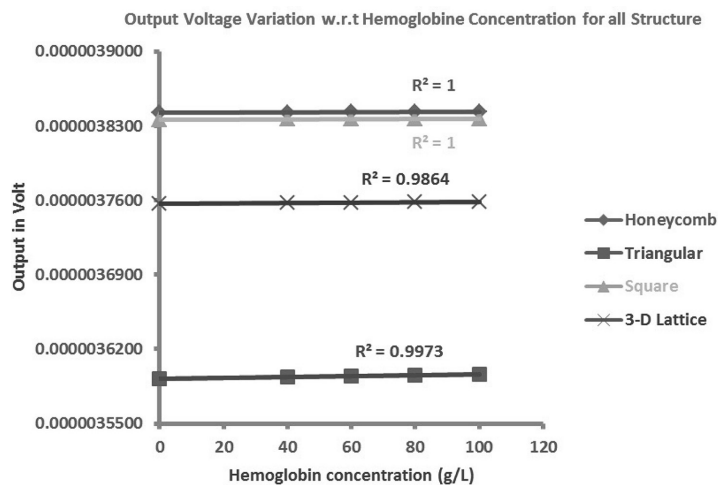


FIGURE 15.21

The variation of transmission light (in volts) with respect to hemoglobin concentration in human blood for different photonic structures.

analyzing the graph, it is clear that for honeycomb and square photonic structures, using AlGaSb material for background materials is best suitable for the measurement of hemoglobin in human blood as it shows the value of $R^2 = 1$. Here, the simulations are performed for 0, 40, 60, 80, and 100 g/L, and the output voltages are varied from 0.0000038422 to 0.0000038433 V for honeycomb photonic structure, from 0.0000035920 to 0.0000035961 V ($R^2 = 99.73$) for triangular, from 0.0000038358 to 0.0000038369 V for square, and from 0.0000037567 to 0.0000037585 V ($R^2 = 98.64$) for 3D photonic structure.

Glucose Concentration in Intralipid:

Estimation of glucose in intralipid is proposed in Palai et al. (2015) using the PWE simulation method by taking a radius of air hole is 300 nm and a lattice constant of 1 μm in a square photonic structure using silicon as a background material.

In this work, the background material is taken as AlGaAs with the absorption coefficient $\alpha = 51,605$ for all types of photonic structure, but radius air holes in honeycomb structure is 200 nm, whereas in triangular and square structure, the radius is taken as 400 nm. By analyzing the graph for both the bandgap variation and output energy with respect to glucose concentration in the [Figures 15.22](#) and [15.23](#), all types of photonic structure possess almost similar result of $R^2 = 99.9$. Here, the simulations are performed for 0, 25, 50, 75, 100, 125, 150, 175, 200 mg/dL of glucose concentration and the output voltages are varied from 0.0000003940 to 0.0000003947 V ($R^2 = 99.92$) for honeycomb photonic structure, from 0.0000003683 to 0.0000003711 V ($R^2 = 99.97$) for triangular, from 0.0000003902 to 0.0000003924 V ($R^2 = 99.93$) for square, and from 0.0000003852 to 0.0000003867 V ($R^2 = 99.97$) for 3D photonic structure.

Cygel:

In Palai et al. (2012), cygel strength at 37°C and 4°C is measured using 2D PC under the PWE technique. The simulation is carried out for different strengths of cygel such as 100%, 115%, 130%, and 145% to obtain the different bandgaps in a 2D square

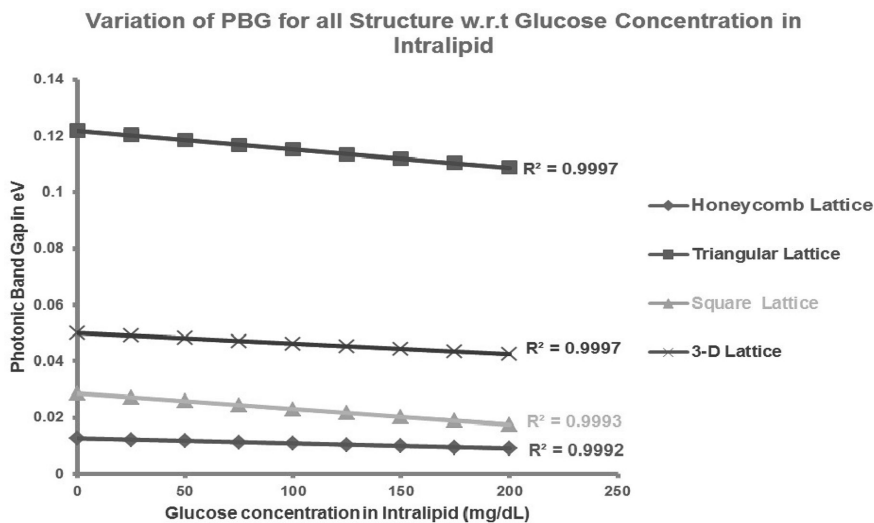
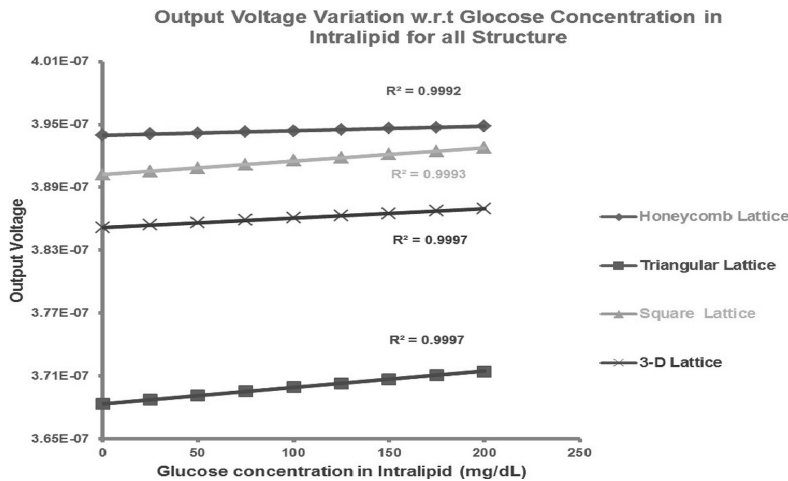


FIGURE 15.22

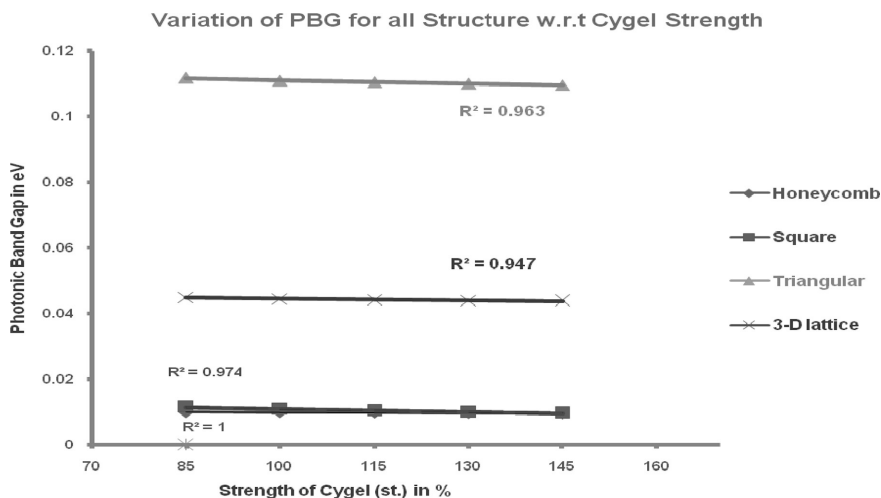
The variation of PBG width with respect to glucose concentration in intralipid for different photonic structures.

**FIGURE 15.23**

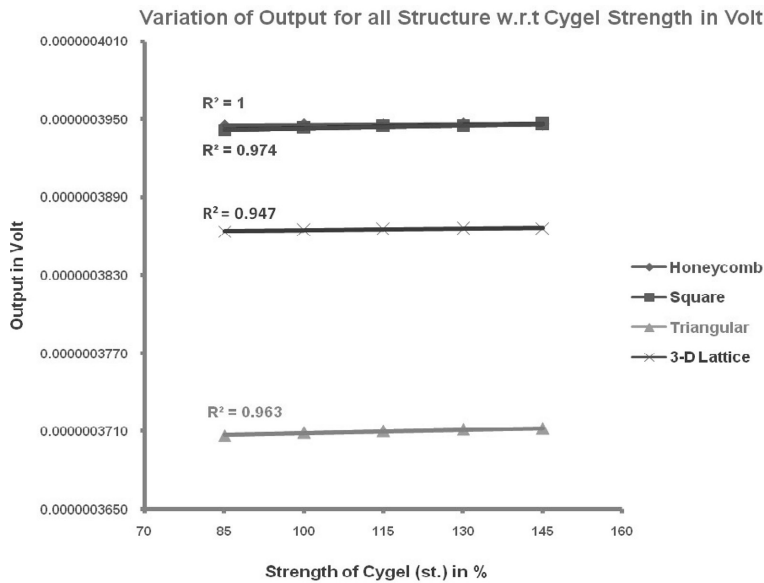
The variation of transmission light (in volts) with respect to glucose concentration in intralipid for different photonic structures.

lattice, which decides the different light intensity at the output when 589 nm of light is incident on the holes (diameter of 0.8 μm) of the square lattice.

In this work, same AlGaAs material is taken for the background material to measure the cygel strength in aqueous for all types of 2D and 3D photonic structures. Also, by analyzing all the structures in the PBG and output light energy graph in the [Figures 15.24](#) and [15.25](#), it is found that the honeycomb structure is best suitable for the measurement of same. Here, the simulations are performed for 85%, 100%, 115%, 130%, and 145% of cygel strength, and the output voltages varied from 0.0000003946 to 0.0000003947 V for honeycomb photonic

**FIGURE 15.24**

The variation of PBG width with respect to Cygel strength (in percentage) for different photonic structures.

**FIGURE 15.25**

The variation of transmission light (in volts) with respect to Cygel strength (in percentage) for different photonic structures.

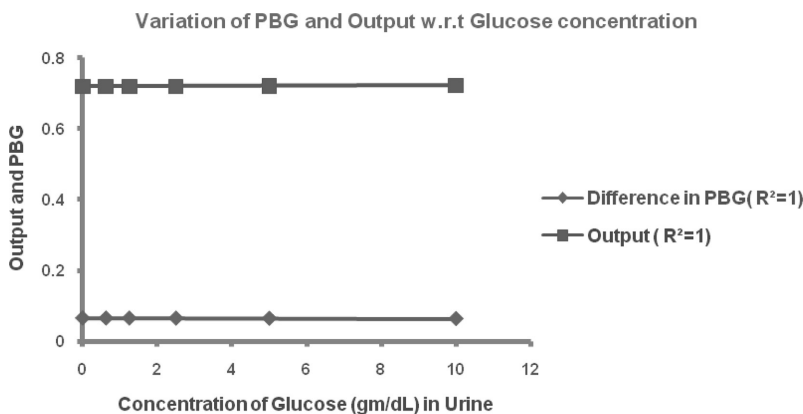
structure, from 0.00000037070553 to 0.00000037122113 V ($R^2 = 96.3$) for triangular, from 0.000000394189 to 0.000000394634 V ($R^2 = 97.4$) for square, and from 0.00000038638451 to 0.00000038661887 V ($R^2 = 94.7$) for 3D photonic structure.

Glucose:

One-dimensional polymer metamaterial is proposed by Sethi et al. (2018) at 589 nm to measure the amount of glucose, urea, and NaCl in human blood using FDTD method. By this, the variation of electric field propagation as well as light intensity is investigated, which varied linearly with the different parameters. This work is different from the previous as it used the FDTD method, which deals with the electric field propagation not from the computation of PBG but from the direct emerging from output. Here the structure has the positive polymer material at the middle of thickness 30 nm, whereas both sides having a thickness of 60 and 110 nm of type negative. The samples to be measured are fed into the middle layer at the light wavelength of 589 nm. Keeping the both side layers as constant, the peak variation of electric field is computed from the second or middle layer. The peak intensity variation corresponding to each sample is computed to yield the corresponding result.

Glucose in human blood is measured in Palai et al. (2018) using a 2D photonic metamaterial at 2 GHz frequency. In this work, silicon and polymer are used as a background material for validation where 3×3 air holes are etched. The variation of S11 parameter is taken into account while simulation by 2D finite element method. The structure contains a 3×3 cylindrical hole having a height of 5 μm and a radius of 10 μm where lattice spacing is taken as 50 μm .

Using 2D PC-based optical sensor, glucose concentration from urine is proposed in Sharma and Sharan (2014) considering the light wavelength of 1530–1565 nm. As in Sharan et al. (2014), same MEEP and MPB tools are used for

**FIGURE 15.26**

The variation of transmission light (in volts) and PBG width with respect to glucose concentration in human urine for different photonic structures.

simulation. It is a noninvasive method to examine the presence of glucose in human urine to treat “glycosuria,” which is a serious indication of diabetics. Here, a 2D square array of dielectric rods in air with a line defect is used for the same with the specification such as a lattice constant of $1\ \mu\text{m}$, a radius of rod of $0.19\ \mu\text{m}$ with a dielectric constant of Si rod of 12, wavelength of light source of $1550\ \text{nm}$ with a shape of Gaussian pulse of center frequency at 0.4 and a pulse width of 0.3.

In this work, considering glass as a background material for a triangular PCS, a urine–glucose sensor is investigated. The principle of getting the equivalent light variation at the sensor output corresponding to PBG variation is obtained by the PWE method. After getting the light intensity at output of the structure, the equivalent output voltage is collected from a photodetector. Here, the width of the PBG and the output equivalent voltage varied linearly ($R^2=1$) with respect to the glucose concentration as shown in Figure 15.26. The simulations are taken for the concentration of glucose in human urine as 0, 0.625, 1.25, 2.5, 5, and 10 (in mg/dL), and the corresponding output voltages are varied from 0.719886758 to 0.721870732 V.

15.5 Conclusion

A thorough computation manipulates with PCS using the PWE method to determine the concentration of hemoglobin in human blood, sucrose in PAM hydrogel, glucose in intralipid, Cygel strength in aqueous, glucose in human urine, and so on. The investigation is made through both 2D and 3D PCSs. The outcomes of the upshot are combined with proteus simulation to exhibit the output potential. As the regression factor (R^2) is more than 99% for most of the cases, the accurate investigation can be realized for suggested biomedical specimen.

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